CRANFIELD UNIVERSITY

João Pedro Corrêa Delgado

SYSTEMIC MODELLING APPLIED TO STUDYING OUBREAKS OF EXOTIC ANIMAL DISEASES

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PhD/MPhil

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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD.

ABSTRACT

Context and rationale – This work originates from policy priorities established within Defra to manage exotic animal diseases (EAD); specifically to understand the causes of low probability events, and to establish contingencies to manage outbreak incidents. Outbreaks of exotic animal diseases, e.g. FMD, CSF and HPAI, can cause economic and social impacts of catastrophic proportions. The UK's government develops and implements policies and controls to prevent EAD and thus minimise these impacts. Control policies to achieve this are designed to address the vulnerabilities within the control systems. However, data are limited for both the introduction of an EAD as well as its resurgence following the disposal of infected carcasses, i.e. the pre-outbreak and post-outbreak phases of an EAD event. These lack of data compromises the development of policy interventions to improve protection. To overcome these data limitations, predictive models are used to predict system vulnerabilities.

Methodology – Conventional predictive methods use two approaches; qualitative approaches to develop descriptive overviews of the entire system, and quantitative methods to analyse specific exposure pathways. Each method fails to provide a complete analysis of the system as well as failing to achieve connectivity between description and analysis. The result is that there is an incomplete understanding of the causes of EAD transmission even when the best available knowledge. Thus, outputs produced by conventional models cannot determine the vulnerabilities within established controls. The research presented here develops a method to apply systemic models to overcome these limitations.

A *bottom-up* approach is used within this study to develop systemic models for EAD, which produce comprehensive analyses of exposure. Using systemic models for this problem establishes *i)* the relationship between cause and effect for events and pathways that influence EAD transmission and the system's behaviour, as well as generates (*ii)* insights into all pathways and events that influence transmission and exposure to EAD, regardless of the perceived likelihood of impact. This analysis of the entire system structure provides sufficient detail to identify key vulnerabilities in the controls.

Output and conclusions – The systemic models presented in this thesis:

- Compare all exposure pathways based on the influence they exert on the overall vulnerability to an EAD;
- Produce an unbiased assessment of exposure pathways and events that are responsible for transmission;
- Provide an understanding of system behaviour that generates insights to improve intervention strategies, e.g. for low probability events.
- Adds to the range of tools available for risk analysts to improve their ability to detect vulnerabilities in EAD controls.

This research demonstrates how systemic models can provide an analysis of the entire system from its structure to the key vulnerabilities. Improvements identified from these insights are likely to reduce significantly the vulnerability to EAD by managing critical control points (CCP). Application of systemic models to the pre-outbreak and post-outbreak phases achieves:

- An overview of the drivers of exposure;
- Identifies specific activities and pathways of exposure responsible for generating high-level risks and
- Produces additional descriptive information on the causes of failure responsible for exposure.
- Enables the development of more informed policy interventions.

Keywords:

Policy development; Carcass disposal assessment, Import risk assessment, Low probability events, Risk mitigation strategies

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LIST OF ABBREVIATIONS

CU	Cranfield University
EAD	Exotic Animal Disease
RA	Risk Assessment
IRA	Import Risk Assessment
CDA	Carcass Disposal Assessment
Defra	Department for the Environment, Food and Rural Affairs
OIE	World Organ for Animal Health
EFSA	European Food Standards Agency
VLA	Veterinary Laboratory Agency
UK	United Kingdom
FMD	Foot and Mouth Disease
FMDv	Foot and Mouth Disease Virus
CSF	Classical Swine Fever
CSFv	Classical Swine Fever Virus
BT	Bluetongue
HPAI	Highly Pathogenic Avian Influenza
BSE	Bovine Spongiform Encephalopathy
DNV	Der Nordske Veritas
LPE	Low probability events
SIS	Simple incursion scenarios
CIS	Complex incursion scenarios
FEP	Feature, events and Processes
ATSDR	Agency for Toxic Substances & Disease Registry
NIOSH	National Institute for Occupational Safety and Health
NPI	National Pollutant Inventory
BioNZ	Biosecurity New Zealand

GLOSSARY

Barrier	Any obstacle reducing the chances of disease transmission, these may be physical and biological barriers and activities performed
Barrier Failure rate	Represent the frequency of barrier failure events associated with a specific process
Bottom-up model	Modelling technique, based on the description of the system where system behaviour and pathways systems emerges for a series of rules used to define the EAD agent transmission characteristic
Carcass disposal assessment (CDA)	Predictive study targeting the impact of carcass disposal during the post-outbreak phase or post t2 phase
Diagonal cell	In the interaction matrix, it represents a network node. In the diagonal cell are also included the sources and receptor nodes
Disease free status	The OIE, mandated by the WTO, officially recognises disease-free areas of countries for trade purposes
Disease spread model	Predictive study targeting transmission during the outbreak phase or $t_{0\text{-}2}$ phase
Events or barrier failure events	Represent a situation or activity causing the preventative barriers (natural and man-made) associated with a specific process to fail in the detection and elimination of the disease agent, leading to a situation in which transmission is possible.
Exotic Animal Diseases (EAD)	Disease agents included in the list of notifiable disease by the OIE
Expert-based model	A model that relies exclusively on expert opinion a source of information to describe the system behaviour and evaluate risks
Feature Events and Processes (FEP) list	Method of recording data, capturing information on all system components and variables, and expert assumptions providing a auditable trail of information
Features	Represent system components where the disease agent may be present. In these models Feature includes all sources, all receptors and all component of the system where the disease may be present at any one time.
Hazardous agent	Substance or biological entity liable to cause harm to a receptor: including EAD agents and other chemical, biochemical and biologic agents
Import risk assessment (IRA)	Predictive study targeting transmission during the pre-outbreak phase or pre t_0 phase
Incidence	Represents the frequency of a process

Off-diagonal cell	In the interaction matrix, these represent an adjacent connection between two network nodes. Each off-diagonal cell is associated with a process (potential transmission) and an event (causing barrier failure) and therefore a process/event.
Pathways system	All available pathways of exposure that form links between source and receptor for a specific pathogenic agent
Predictive modelling	Studies developed to predict the outcome of one or multiple events. These models may be computer-based or expert-based
Process	Represents an activity and/or movement (e.g. live animals, food goods, people, etc.) which present the potential for transmission of the disease agent
Process/event	Represents the interactive behaviour between a process that potentially enables disease transmission between two features and the barriers protecting transmission
Risk factor	Any form of EAD transmission, e.g. livestock, meat produce, fomites, vectors, other host)
Scenario	Character of a pathway of exposure, through the description of the sequence of event uniting the disease source to a susceptible receptor
Scenario-based model	Computer based model focussing on one or multiple pathways of exposure. These models use a binomial or an event tree based model to estimate the likelihood or quantity of the agent exposed through a pathway
System	The source-pathway-receptor relationship
System behaviour	The interactive relationship between an EAD agent and the source-pathway-receptor
Systemic Analysis	A study aiming to analyse the full extent of the source-pathways-receptor relation, by analysing all pathways of exposure connecting source to receptor, regardless of likelihood and impact, that are considered within the adopted definition of system
Top-down model	Modelling technique, where the assessor or experts based on their perception of system behaviour, define the pathway(s) or pathways system used to estimate the impact of exposure

1 INTRODUCTION

The work presented in this thesis addressed the subject of exotic animal diseases, recognised and categorised by the World Organ for Animal Health (OIE) as caused by disease agents posing significant health, economic and social concern (OIE, 2011a). This is an international issue, which considers multiple disease agents and affects multiple countries, worldwide. The context, in which it is addressed here, relates to countries classified by the OIE as disease free, where an outbreak results in the loss of such status with trade implications, which can escalate the economic impacts beyond those associated disease control (Otte et al., 2004; Scudamore et al., 2002; Morgan and Prakash, 2006).

It falls within any government's role to protect its population from events causing severe economical and health impacts (Otte et al., 2004). The development of strategies to prevent and eradicate disease agents varies between countries, influenced by geographical characteristics, and political and economic conditions. Here we analyse the approach from the UK government for intervention in case of an EAD outbreak, although acknowledging that issues identified may be common to EAD control for multiple countries.

From a policy development perspective, an EAD outbreak progresses across three phases. These are: (i) a pre-outbreak phase involving the introduction of an EAD into the UK; (ii) an outbreak phase, involving the spread of the disease agent through the UK and; (iii) a post-outbreak phase, which involves the disposal of the carcasses of the infected animals. A review of the research literature indicates that there are significant limitations in the research literature regarding the pre-outbreak and post-outbreak phases. These gaps represent limitations in the government's capacity to understand the full extent of the source-pathway-receptor relationship associated with these phases. As a result, this limits the government's capacity to develop strategies to minimise the likelihood of exposing livestock to an EAD agent. Consequentially, existing policies tend to focus on known threats with the potential to overlook the contribution to exposure from characteristics of the source-pathway-receptor relationship that have so far evaded analysis within the existing predictive models and reports associated with EAD outbreaks.

This thesis presents work that develops the application of expert-based systemic models to generate a better understanding of the source-pathway-receptor relationships associated with the pre-outbreak and post-outbreak phases. In doing so, these models generate an improved understanding of system behaviour and identify the drivers of exposure that pose a significant influence in the development of EAD outbreaks. The output of expert-based systemic models provides information on these two phases of an EAD outbreak. In short, these improve the information and capacity to develop policies that significantly reduce the likelihood of livestock exposure to an EAD across all outbreak phases.

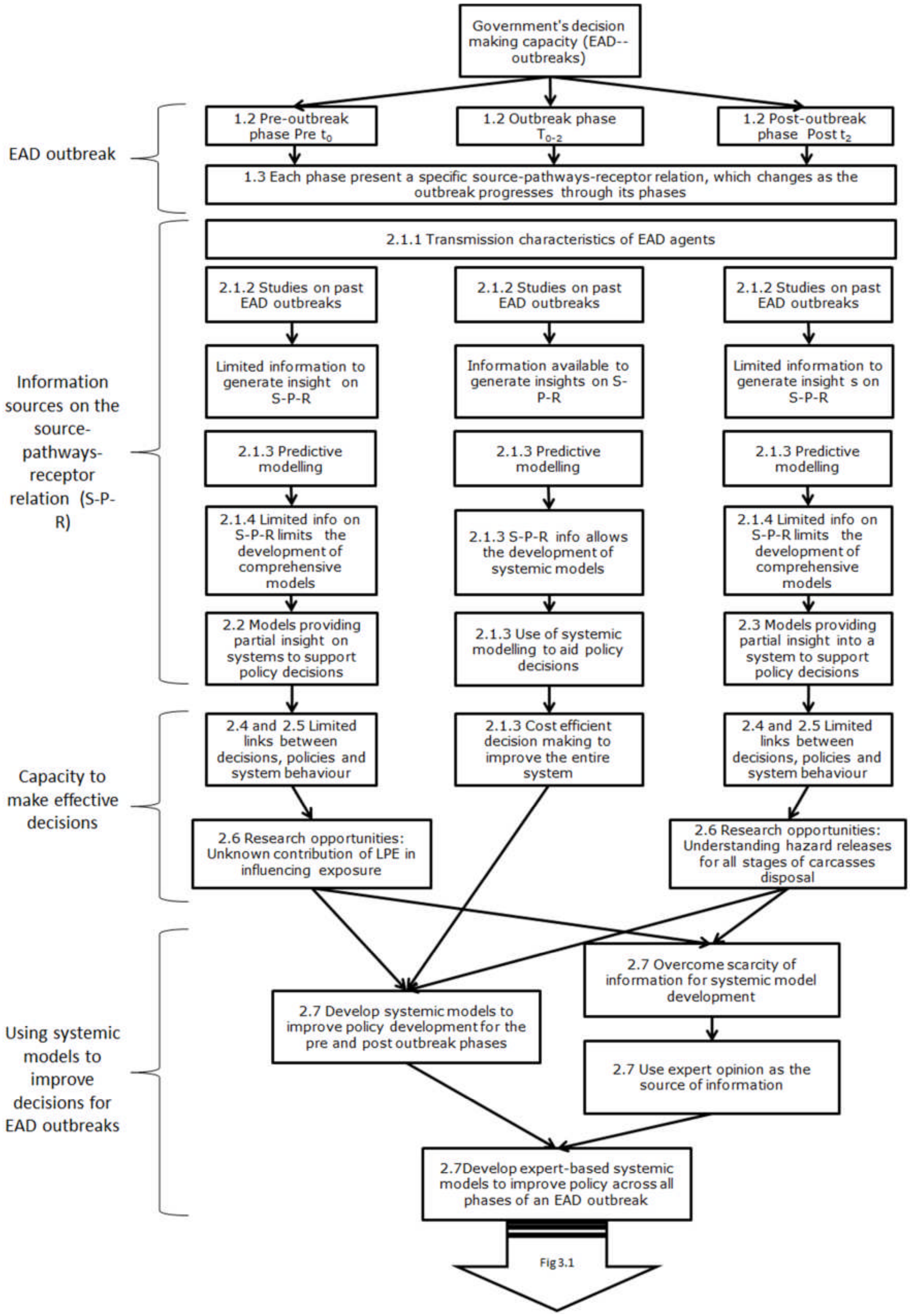

Figure 1.1 Flowchart of the introduction and literature review

[key] Representation of the research literature, identified research opportunities and rationale supporting the research objectives.

1.1 Exotic animal diseases

Exotic animal diseases (EAD) consist of a group of diseases recognised by the World Organ for Animal Health (OIE) as those that pose greatest health, economic and social concern. A complete list of diseases that fall under the EAD denomination is available (OIE, 2011a). Other names include notifiable diseases and trans-boundary diseases. This categorisation results from international recognition of their attributes that present the potential to cause significant social and economic impacts.

"those that are of significant economic, trade and/or food security importance for a significant number of countries; which can easily spread to other countries and reach epidemic proportions; and where control/management, including exclusion, requires cooperation between several countries". (Otte et al., 2004)

The group of EAD includes an array of animal diseases caused by a variety of pathogens. These may affect multiple hosts and have differing transmission attributes, e.g. airborne spread for Foot and Mouth Disease (FMD) or arthropod vectors for African Swine Fever and Blue Tongue Disease (OIE, 2011a; Kitching et al., 2007; Cottam et al., 2008b; Kitching et al., 2005; Wieland et al., 2011). Contrary to popular belief, there is no evidence that the ongoing technological and policy developments have achieved increasing protection for developed countries against EAD outbreaks (Otte et al., 2004; EFSA, 2006; Thiermann, 2005). Moreover, a study by the European Food and Standards Agency (EFSA, 2006), argues that the circumstances causing the 2001 FMD outbreak remain unchanged. Therefore, there are no indications that the risk of outbreaks is decreasing. Furthermore, geographical features, free trade and ethnic, social and cultural factors may increase the risk of exposure to an EAD pathogen. This is increasingly true for European countries. Recent examples of EAD outbreaks in the United Kingdom (UK) include:

- Bovine spongiform encephalopathy (BSE) (Smith and Bradley, 2003; Defra, 2009a; Phillips et al., 2000; Donnelly et al., 1999);
- Foot and mouth disease (FMD) (Defra, 2011b; Anderson, 2002; Scudamore et al., 2002);
- Classical swine fever (CSF) (Gibbens et al., 2000; Sharpe et al., 2001) and;
- Highly pathogenic avian influenza (HPAI) (Defra, 2007c; FAO, 2006).

EAD outbreaks are associated with high economic impact and therefore EAD represent a group of diseases that require special attention on behalf of government and international animal health agencies.

1.1.1 Government's role in strategic planning and policy

It falls within government responsibility to protect the population from the impact of an outbreak. Despite the array of pathogens included in the group of EAD, the UK government adopts a similar policy towards each of them. Cost-benefit analyses suggest that there are economic advantages in maintaining a disease free status, whilst ensuring sustainable opportunities for international trade (Otte et al., 2004). This trade-off influences disease control strategies at national and international levels. Developed countries, such as the UK, make considerable costly efforts to ensure the disease free status is maintained, i.e. preventing the exposure of livestock to an EAD agent.

Preventive disease control strategies include EAD control at its source, a policy that considers global eradication. However, this requires considerable investment in controlling and eliminating the disease in developing countries (EFSA, 2006; Scoones and Wolmer, 2006). Furthermore, disease eradication has a low success rate. Rinderpest, which was a devastating cattle plague, remains as the single successful example of eradication (Scoones and Wolmer, 2006; Normile, 2008). The successful eradication of Rinderpest resulted from a high level commitment and a costly and long-term investment (Kitching et al., 2007; Kitching et al., 2005; EFSA, 2006). While disease eradication remains typically a non-viable solution, the OIE supports comprehensive plans to deal with the threat of EADs at a national level (Otte et al., 2004; Defra, 2009b; Defra, 2011a; Morgan and Prakash, 2006). These assure a high-level of prevention and preparedness through the development and the application of prevention plans (Defra, 2009b; Morgan and Prakash, 2006; EC, 2004; AHA, 2005). Prevention plans require the application of controls, such as trade and health certificates, to avoid disease incursions into disease-free countries and routine monitoring activities to ensure quick detection of infected livestock (Defra, 2011a). When prevention fails and livestock is infected, it activates contingency measures. These are essential activities included in cost-effective programs to control and eradicate disease, at a national or regional level (Defra, 2009b; Geering et al., 1999).

The policies developed and applied by countries which are disease free or currently dealing with an EAD, including the UK, aim to prevent and minimise the social and economic impacts that result from an EAD outbreak (Otte et al., 2004; Scudamore et al., 2002; Morgan and Prakash, 2006; Bender et al., 2006; EA, 2001). These involve a continuous process of policy and planning development. Scientific data and cost benefit analysis reveal the importance of maintaining tight control over EAD pathogens (Donnelly et al., 1999; Anderson, 2002; Scudamore et al., 2002; Defra, 2008b; Defra, 2006). However, this process is influenced by economic, social and environmental factors, which may result in a weakening of the controls in place (Thiermann, 2005; Aven, 2009). Therefore, matching the constant rise in threats with a strategic and technological response is a requirement that needs to be recognised.

The development of efficient strategic responses requires insight into the factors and mechanisms of disease transmission. This information allows an understanding of the behaviour of the EAD agent during the EAD outbreak (Morris, 1995; Pearce, 1996; Krewski et al., 1990). Thus, it provides insights on how to control and minimise the impact of outbreaks.

1.2 EAD outbreak

An EAD outbreak comprises an interval between the infection of the first premises across to the elimination of the last infected animal or dangerous contact (Defra, 2009b). Figure 1.2 displays the time line of an EAD outbreak for the UK. The moment the first farm becomes infected is represented by t_0. The time interval that follows, [t_0, t_1] represents the spread of the EAD agent to other premises which occurs prior to the detection of the EAD agent. This is known as the silent spread of the disease (De Vos et al., 2004; Dubé et al., 2007). The silent spread of the disease finishes with the detection of the EAD agent within a livestock premises. In Figure 1.2, t_1 represents the moment the presence of an EAD is detected. Detection of an EAD puts in motion a contingency plan involving a standstill policy, which bans all movement of animals, animal products and by-products from the premises (Defra, 2009b; Dubé et al., 2007). These measures eliminate inter-farm contact to reduce the likelihood of further spread. Alongside the standstill policy, the government adopts a strategy to eradicate the disease agent. The time interval that follows, [$t_{1,}$ t_2] represents the EAD spread whilst contingency measures apply until the eradication of the EAD agent (Defra, 2009b; De Vos et al., 2004; Dubé et al., 2007). The outbreak ends upon confirmation of the elimination of the EAD agent from UK premises (Defra, 2009b). This moment is represented by t_2. Therefore, the interval [t_0, t_2] represents the duration of an EAD outbreak.

The interval representing the EAD outbreak [t_0, t_2] is associated with the presence of the EAD agent within premises. However, during the evolution of an EAD outbreak there are circumstances when the EAD agent is, whilst absent from premises.

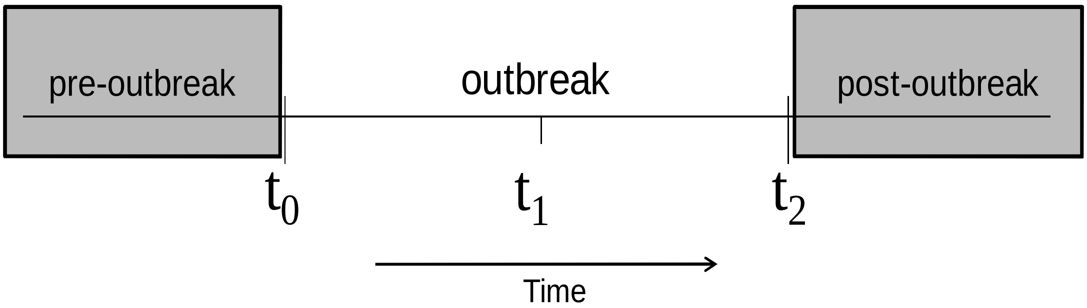

Figure 1.2 Disease outbreak timeline

The UK government takes the responsibility to coordinate efforts to contain and eliminate the EAD agent during an outbreak. Similarly, it is the government's responsibility to coordinate preventive measures to avoid EAD introduction (Defra, 2011a). It is also its responsibility to prevent resurgence of the disease following an outbreak, which includes monitoring the residual products resulting from disposal of carcasses (Defra, 2009b). Therefore, when defining the timeline of an EAD outbreak from the government's perspective, it is necessary to expand the definition beyond the interval that considers the presence of EAD agents in livestock farms. Figure 1.2 displays two further intervals represented by grey rectangles. The first interval, displayed to the left of t_0, represents the pre t_0 phase. It takes place before the infection of the first premises and represents the transmission of an EAD agent from a foreign country into the UK (Defra, 2010b; OIE, 2011c). This represent the introduction of the EAD agent and is defined here as the pre-outbreak phase. A remaining interval displayed to the right of t_2 represents the post-t_2 phase. This phase involves monitoring the residual products derived from carcass disposal activities to ensure the resurgence of the disease is not possible (EA, 2001; Ritter and Chirnside, 1995; Drummond, 1999; Marsland, et al., 2003). This represents the prevention of disease resurgence from disposed carcasses and is defined here as the post-outbreak phase. Therefore, from the government's perspective, an EAD outbreak occurs in a sequence of three phases. These are:

- The pre-t_0 interval representing the pre-outbreak or pre-t_0 phase where focus is on preventing the introduction of an EAD.
- The $[t_0, t_2]$ interval representing the outbreak phase or t_0-t_2 phase where focus is on preventing EAD spread and promoting containment and elimination (Defra, 2007c; Defra, 2011a).
- The post-t_2 interval representing the post outbreak phase or post-t_2 phase, where focus is on preventing resurgence of the EAD from disposed carcasses to ensure its elimination.

All phases represent EAD transmission according to the risk assessment paradigm of source-pathway-receptor (Haas et al., 1999; Vose, 2008). The paradigm provides the basis for defining the relationship between the source of the disease agents, the pathways of exposure and the impact to receptors during each of the three outbreak phases. The paradigm of source-pathway-receptor provides the framework to describe the system under scope. Here, the definition of system is: **(i) the collection of entities influencing transmission, which by interacting with a specific EAD agent establish a connection that links the source to the receptor and (ii) the controls and regulations in place that these entities and stakeholders have to uphold in order to sever those connections and prevent exposure.** This definition of system, whilst generic, defines a boundary that excludes from it all entities and controls not relevant to transmission during a specific outbreak phase. Entities are defined under system's language as system components. Under this definition of system, any system component influencing transmission must be included. Therefore, the list of system components may include entities, as diverse as the environment (soil, air and water), livestock and wildlife, livestock lorries and humans population (veterinarians, fieldsman and general population). Similarly, any pathway of exposure influencing transmission of a disease agent from source up to exposure must be included, and therefore a system representation must include all pathways of exposure. Here, **pathways system stands for the collection of all pathways of exposure available within a system**

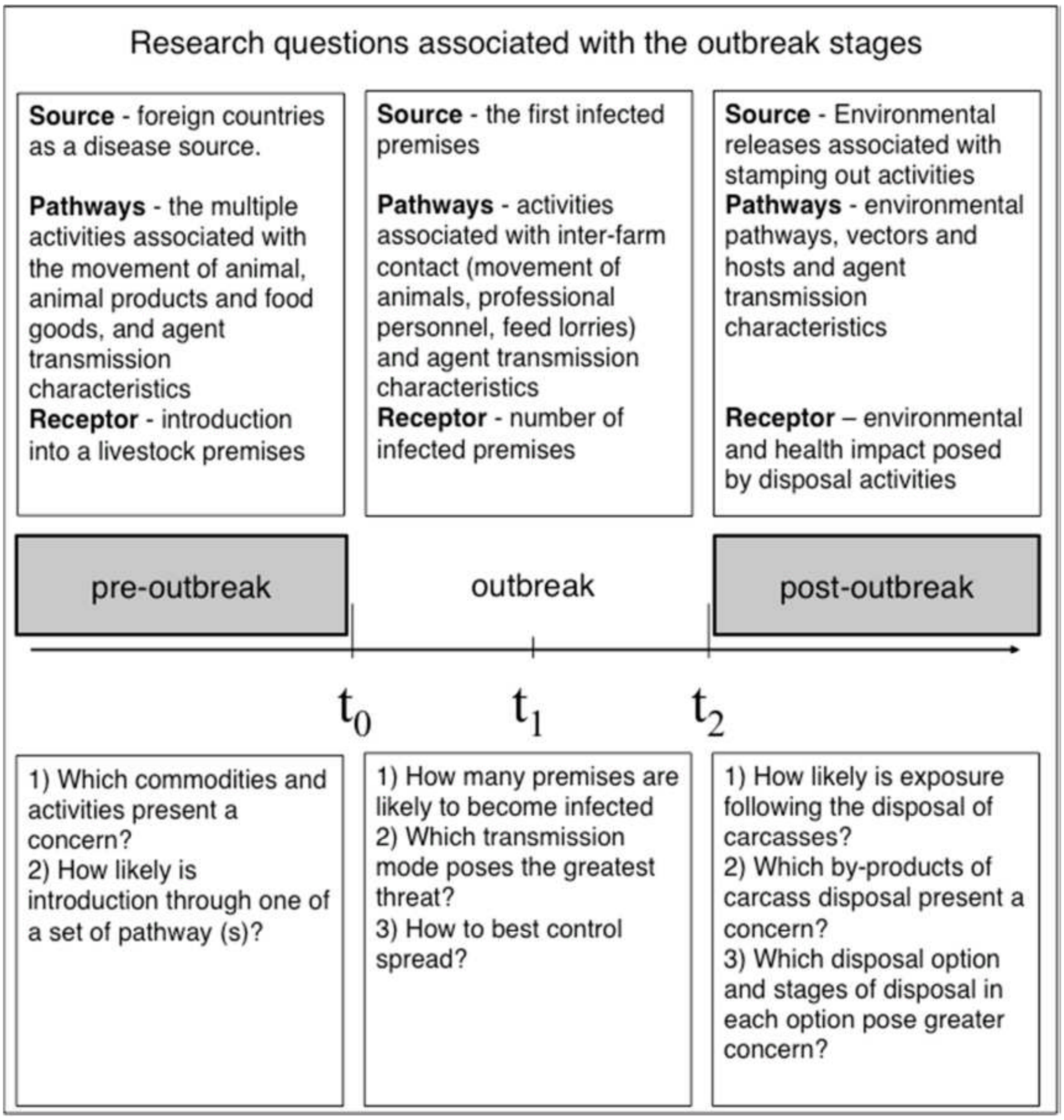

Figure 1.3 Source-pathway-receptor relation and research question associated with the pre-T_0, T_0 - T_2 and post T_2 phases of the outbreak

Figure 1.3 describes, summarily, for each outbreak phase the source-pathway-receptor and the research questions conventional associated with epidemiologic studies (these are analysed in further detail in Section 1.3). Each phase (from left to right) corresponds to a different source-pathways-receptor and to studies focussing on answering a specific set of research question. These differences influence the definition of exposure and how its impact is measured during outbreak each phase. For example, the pre-outbreak (pre t_0) phase has a fixed impact, which is the infection of the first livestock premises (Defra, 2011a). However, for the outbreak (t_0-t_2) phase, impact is associated with the number of livestock premises infected and geographical spread of the EAD agent (Dubé et al., 2007). This generates a phase specific context to EAD transmission, which influences the characteristic of the source-pathway-receptor relationship - and the mechanism and controls driving exposure - under scope in studies addressing exposure in a specific outbreak phase.

The outbreak phase specific context to EAD transmission reveals system components that are influential for one phase, which may not be influential for the remaining ones and vice versa. An analysis of the system focussing on the system components reveals changes to its composition as the outbreak progresses through its phases (Section 1.3). This is true for the components representing the source of an EAD during each phase, as is for the pathways of exposure and the receptor. Therefore, contextualisation influences the composition of the system under assessment. Figure 1.3 displays the source-pathway-receptor for the three outbreak phases (top). In the definition of source-pathway receptor relation:

- Source represents the source of the EAD agent considered for each phase (Haas et al., 1999; Vose, 2008).

- Pathway stands for the pathways system and represents all available pathways of exposure that result from the interaction between an EAD agent and the system components. Therefore, pathways of exposure depend on the transmission characteristics an EAD agent (Haas et al., 1999; Vose, 2008).
- Receptor represents the livestock population susceptible to exposure and harm by an EAD.

The source-pathway-receptor relationship changes as the EAD outbreak progresses through its timeline. This results in a progressive change to the system's composition. These changes occur at t_0, when the concern moves from preventing EAD introduction to controlling its spread and at t_2, when the concern moves from controlling the spread to preventing resurgence of the disease, thus minimising the environmental and health impacts of carcass disposal. Furthermore, the specific context in which transmission is assessed for each phase suggests the mechanisms and controls posing an influence in exposure to EAD change alongside the systems composition. Consequentially, policies and regulations applied to control EAD transmission for one stage may not apply or be inefficient for the remaining ones. Policy development must consider these changes to ensure effective control strategies are in place across the full length of an outbreak. Following is a description of the system associated with each outbreak phase, focussing particularly on the differences between them.

1.3 <u>Changes to the system as the outbreak progresses</u>

1.3.1 Pre-outbreak (pre- t_0) phase

The pre-outbreak phase (pre-t_0) phase represents the introduction of an EAD from a foreign source of the disease and its exposure to British livestock. Figure 1.4 displays the system involved in the pre-outbreak phase. This diagram is collected from a report produced by Defra, which reviews the controls in place to prevent EAD introduction (Defra, 2011a). The figure represents the system associated with the introduction of a hypothetical EAD, the Dreaded Lurgi. The diagram represents the fundamental principles of the source-pathway-receptor relationship associated with the pre-outbreak phase, i.e. a generic example. These are common to all EAD.

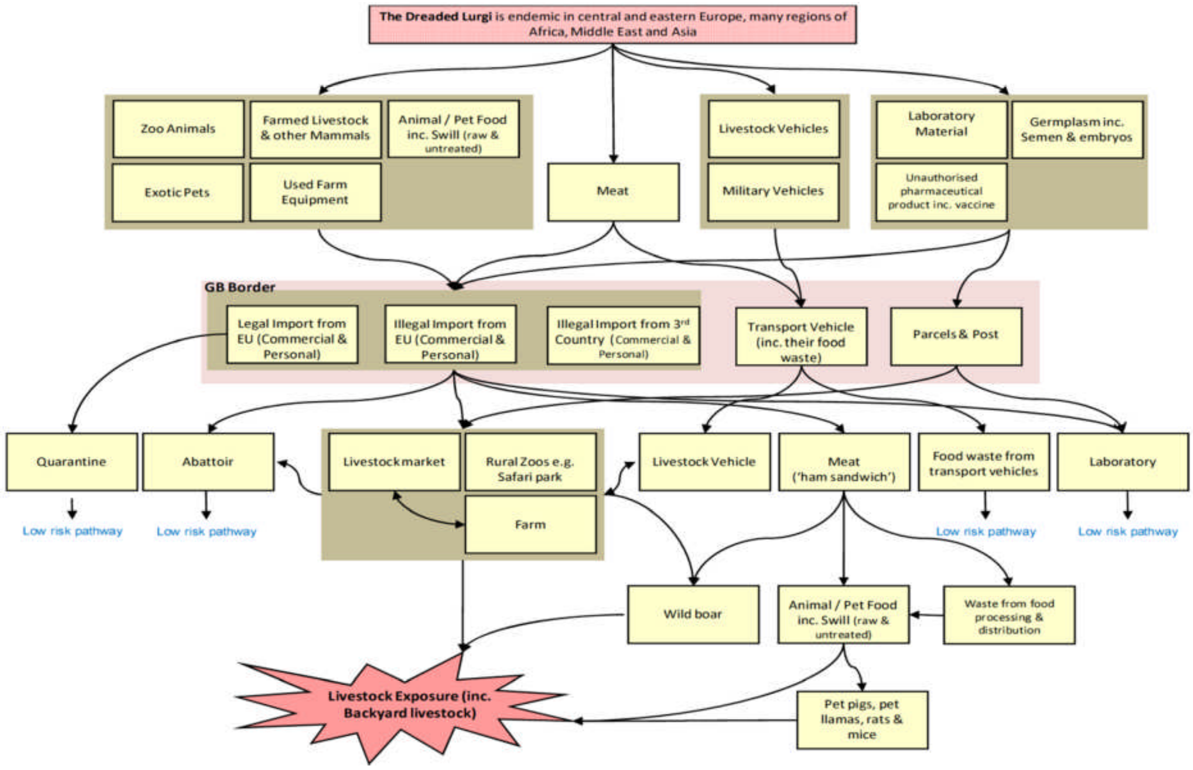

Figure 1.4 Pathways and nodes contributing the introduction of an animal a hypothetical EAD

> [Key] The diagram includes pathways and nodes presenting the highest relative risk for a scenario based on a disease with a hypothetical profile (Defra, 2011a).

Figure 1.4 represents the source of an EAD as foreign countries (outside the UK) where the disease is endemic or undergoing an isolated outbreak (top - pink rectangle). Different diseases may be present in different countries. In principle, an EAD source is within a foreign country (Gibbens et al., 2000; Defra, 2007c; Scudamore, 2002). The exception is an accidental laboratory release of an EAD (Anderson, 2008). A UK based source represents an ongoing outbreak or the deficient elimination of the disease agent from a previous outbreak.

Figure 1.4 represents a pathways system composed of the collection of exposure pathways associated with the activities involved in the transmission of the disease from the source through to the exposure of livestock (yellow rectangles). It is unwise to present a description of all activities involved, as these are EAD agent specific and therefore vary according to the transmission characteristics of the EAD agent considered (OIE, 2011a; OIE, 2011b). Common activities involve legal and illegal imports of meat goods, live animals and animal products, such a germplasm (Defra, 2011a; Defra, 2011c). These imports can also be associated with the livestock industry, retail and food transformation industries or even personal imports. Therefore, there are a large number of activities to consider which reflect a high number of exposure pathways available for EAD introduction. For example, Figure 1.4 represents only the pathways ranked as high risk in the study (Defra, 2011a).

Figure 1.4 represents the receptor, or the impact of exposure as exposure to livestock (Defra, 2011a). This definition confines the impact of exposure to a single event, the exposure to livestock (bottom – pink star). Although not specified in literature, a more detailed description of this event is the infection of one livestock animal, as exposure does not guarantee infection. Therefore, the infection of the first animal (t_0) represents the onset of the next EAD outbreak phase.

1.3.2 Outbreak (t_0–t_2) phase

The outbreak phase (t_0–t_2) phase represents the spread of the EAD agent across British farms. The type of livestock premises, i.e. cattle, poultry or pigs, susceptible for infection and the modes of inter-farm transmission depend on the EAD agent considered (OIE, 2011a; OIE, 2011b). Nonetheless, the system or source-pathway-receptor relationship for the outbreak phase presents fundamental principles that are common to all EAD. Figure 1.5 represents the spread of an EAD following the infection of a livestock premises. This picture is based on the work developed to study the spread of FMD in 2001 following the application of standstill measures (Cottam et al., 2008a). Nonetheless, it represents the fundamental principles of the source-pathway-receptor relationship associated with the outbreak phase.

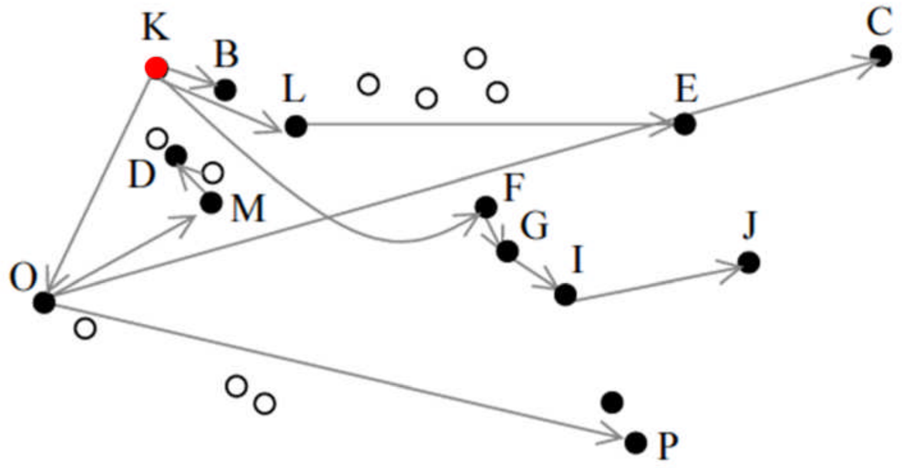

Figure 1.5 Diagram showing the spatial relationship of 14 infected premises

[Key] 14 premises (filled circles) confirmed by laboratory testing and 9 infected premises (clinical observations) that were subsequently found to be negative for virus by laboratory testing (open circles). The originally infected farm represents the source of the disease (red circle). The grey arrows show the direction of transmission events: Based on Cottam et al. (2008a).

Figure 1.5 represents the source of the disease as the first infected premises (Cottam et al., 2008a). This first infected farm (red dot – K premises) is the source of the EAD (Defra, 2007c; Dubé et al., 2007; Cottam et al., 2008a).

Figure 1.5 represents the pathways system associated with activities providing inter-farm contact that allow for the infection of new premises. These are described as transmission events (Cottam et al., 2008a). It is unwise to enumerate the activities involved in inter-farm contact, as these are EAD agent specific and therefore vary according to transmission characteristics of the EAD agent considered (OIE, 2011a; OIE, 2011b). Common activities involve the movement of live animals and of personnel between farms, fomites and the EAD agent transmission characteristics, such as airborne and vector based transmission (Cottam et al., 2008b; Kitching et al., 2005; Dubé et al., 2007; Cottam et al., 2008a; Harvey et al., 2007; Gloster et al., 2010; Garner and Beckett, 2005). In Figure 1.5, the grey arrows represent inter-farm transmission and thus pathways of exposure.

Figure 1.5 represents the receptor, or the impact of exposure, as the number of infected farms and geographical spread of the EAD agent. This represents a generic definition for measuring the impact of the outbreak (Dubé et al., 2007; Garner and Beckett, 2005; Dubé et al., 2006), as it must also consider the number of animals infected and value of these animals (Scudamore et al., 2002; Defra, 2007c). Nonetheless, the definition of impact proposed here relates to the system's principles of disease spread during the outbreak phase, whilst acknowledging that the economic impact of the disease may depend on added economic and policy factors.

1.3.3 Post-outbreak (post- t_2) phase

The post-outbreak phase (post- t_2) phase represents the interval after the elimination of the last infected animal and the EAD agent can no longer be detected on livestock premises. The post outbreak phase results from the adoption of a "stamping out" or a "vaccinate-to-kill" policy to eradicate the disease agent (Defra, 2009b). Historically, these represent the policies adopted by the UK's government during EAD outbreaks (Scudamore et al., 2002; Defra, 2007b). In reality, the implementation of a stamping-out policy occurs following the detection of the disease agent, between t_1–t_2. However, as monitoring of the disposal sites continues after the eradication of the EAD agent (Scottish Executive, 2002), for the purposes of this revision, the resurgence of the EAD agent from the remains of the disposed carcasses is considered as a separate phase. In the post outbreak (post t_2) phase focus is expanded to consider the environmental and health impacts of carcass disposal activities (EA, 2001; Lowles et al., 2002; Pollard et al., 2008a; DH, 2001). Several disposal options are available for the disposal of carcasses. This include disposal by incineration, burial and rendering under varying conditions from highly controlled to open air disposal. Figure 1.6 displays a simplified model of the events taking place during carcass disposal. The figure represents the sources and receptors, illustrating the system or source-pathway-receptor relationship associated with the post-outbreak phase.

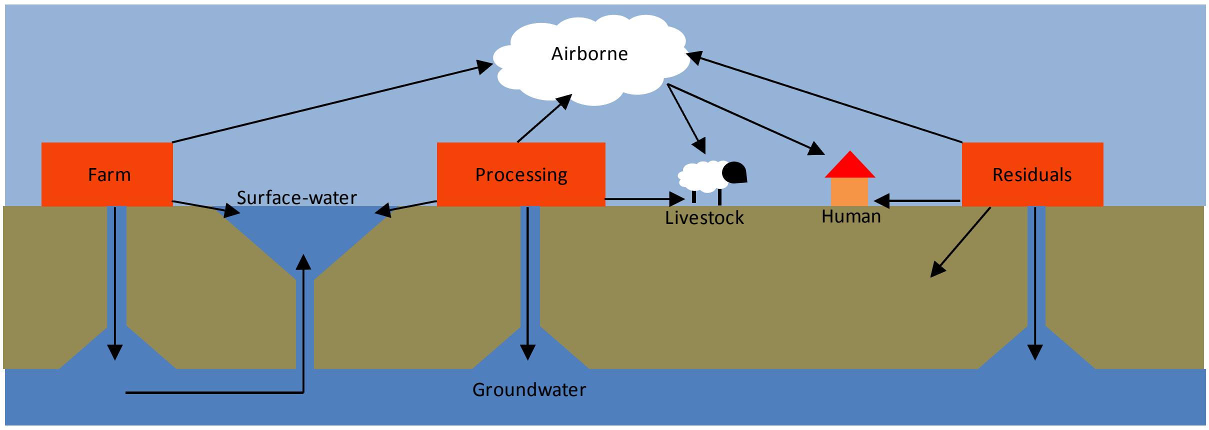

Figure 1.6 the multiple sources of hazardous agents and receptors for the post outbreak (post t_2) phase.

> [Key] The sources (red squares) and receptors (water bodies) associated with the disposal of infected carcasses under a "stamping-out" policy: Black arrows represent possible pathways of exposure and environmental contamination.

Figure 1.6 represents the sources as independent events. The disposal activities include culling activities on-premises, removal of the carcass and transport to a processing site, processing of the carcasses and management of the residual products of processing

(Defra, 2009b; Pollard et al., 2008a; AHA, 2007). Each of these activities represents an isolated event. Therefore, each disposal activity represents a new release of hazards into the environment. Each disposal activity is independent and therefore does not influence the preceding or following ones. Furthermore, the nature of the activities influences the hazardous agents released. This may include the EAD agents alongside other biological hazards, biochemical hazards from carcass decay and chemical hazards from carcass processing, i.e. fuel for incineration (Nutsch et al., 2004). Therefore, the system includes multiple singular release events, occurring at different times and locations.

Figure 1.6 presents examples of pathways of exposure (black arrows) associated with carcass disposal activities. An independent suit of pathways is associated with a particular disposal activity therefore it includes multiple localised pathways systems (Pollard et al., 2008a). For example, Figure 1.6 represents the disposal of carcass as a chain composed of three independent activities. These include the culling of animals on a premises, processing of the carcass at a different location and managing the residual product at a third location. For each activity, occurring at specific location, an independent pathways system represents the interaction between the hazardous agents and the environment (Nutsch et al., 2004). For example, these pathways may include infiltration of the soil, contamination of water sources and air and exposure to wildlife (Figure 1.6).

Figure 1.6 represents a receptor, or the impact of exposure, as environmental contamination and the magnitude of exposure of the livestock and human population to any of the hazards agents released during the disposal activity (Defra, 2011b; Pollard et al., 2008a). This includes a potential resurgence of the disease through exposure of livestock to the EAD agent (Alexandersen and Donaldson, 2004). It also considers the impact in air and water quality and health effect to the human and livestock population resulting from the by-products of disposal (EA, 2001; Lowles et al., 2002).

1.3.4 System changes throughout the progression of an EAD outbreak

This summary describes the events taking place during each outbreak phase and explores the changes in the source-pathway-receptor relationship as the outbreak progresses. The changes to the system result from the difference in factors playing a significant role in EAD transmission. For example, the movement of animals between UK farms is significant in the spread of disease during the outbreak phase (Green et al., 2006; Fèvre et al., 2006; Bigras-Poulin et al., 2006). However, such movements do not influence transmission during the pre-outbreak phase, as all farms are free from the EAD agent. Similarly, these do not influence the environmental contamination during the post-outbreak phase. In conclusion, each outbreak phase represents a unique dynamic in the source-pathway-receptor relationship.

1.4 Policy development across all phases of an EAD outbreak

Acknowledging these differences in source-pathway-receptor relationships carries with it the recognition that information available to support policy decisions is not directly transferable between the three phases of an outbreak. Moreover, it suggests that effective policies to control EAD transmission for one phase may not be effective across all phases. This leads to the conclusion that effective policy development involves supporting decisions with phase specific information.

This work analyses the sources of information available to support the decision across all phases of an outbreak. It identifies the limitations of the existing data to support decisions and develops a solution to overcome them with the aim of improving the policy development capacity and contributing from a more efficient management of EAD outbreaks.

2 LITERATURE REVIEW

2.1 Managing exposure throughout an animal disease outbreak

The policies developed and applied by developed countries, more specifically by the UK, aim to prevent and minimise the social and economic impacts that result from an EAD outbreak (Otte et al., 2004; Scudamore et al., 2002; Morgan and Prakash, 2006; Bender et al., 2006; EA, 2001). The development of intervention strategies finds support in data. The data available in the research literature provides insights on EAD agent transmission characteristics and system behaviour (Morris, 1995; Pearce, 1996). These insights support the development of management solutions to prevent the exposure of livestock to an EAD and thus, minimising the impact of an outbreak (Defra, 2011a; Pollard et al., 2008a; Taylor, 2003; Peeler et al., 2006).

Information on the behaviour of the system across all phases of an EAD outbreak allows for the identification of the factors influencing disease transmission in each phase. This involves analysing all the factors influencing disease transmission and the effectiveness of the controls in place to prevent it, regardless of their perceived influence in the system (Murthy and Krishnamurthy, 2009). This analysis provides information on the mechanism involved in disease transmission (Murthy and Krishnamurthy, 2009; Pearce and Merletti, 2006). Furthermore, it establishes a relation of cause and effect between the factors influencing EAD transmission and the control in place prevent it, and the system's behaviour (Murthy and Krishnamurthy, 2009; Carré and Singer, 2008; Borrett and Patten, 2003). Such insights inform on the most influential factors of a system's behaviour, thus they provide information to support the development of strategies to reduce UK's vulnerability to an EAD.

The information available on the source-pathway-receptor relationships for the three outbreak phases falls into three categories. These are:

- Transmission characteristics of EAD agents
- Studies on past EAD outbreaks
- Predictive modelling

2.1.1 Transmission characteristics of EAD agents

There is a sound body of publications on transmission characteristics. This includes information of the transmission modes, e.g. airborne, direct contact, ingestion and inhalation. These also define the survival of EAD agents and viability outside the host under various circumstances, e.g. temperature, humidity and medium (OIE, 2011b; OIE, 2011b; Brown and Gajdusek, 1991; Weesendorp et al., 2008; De Smit et al., 1999). Defra and the OIE maintain a database that summarises the characteristics of disease agents (OIE, 2011a; OIE, 2011b). Alongside this, there are a large number of studies developed to analyse specific forms of transmission under field and laboratory conditions. Table 2.1 displays a summary of studies associated with the transmission characteristic of CSF under field and laboratory conditions. Such information is also available to other EAD agents. For example, reviews of the transmission characteristics of the FMD and HPAI virus are also available (Alexandersen et al., 2003; Grubman and Baxt, 2004; Van Oirschot, 1999; IFST, 2004; Alexander D. J., 2001; Moennig, 2000).

Modes of transmission	**Classic Swine Fever**		
	Proven in Lab	Disease Import	References
Animal movements	+	+	(Moennig, 2000; Terpstra, 1987; Elbers et al., 1999; Artois et al., 2002; OIE, 2002; AHA, 2009; Stegeman et al., 1997)
Transport vehicles	+	+	(Weesendorp et al., 2008; Moennig, 2000; OIE, 2002; AHA, 2009; Stegeman et al., 1997)
Human contacts	+	+	(Terpstra, 1987; OIE, 2002; Stegeman et al., 1997; Ribbens et al., 2004)
Meat based food products	+	+	(OIE, 2002; OIE, 2002; Ribbens et al., 2004)
Wild boar	+	+	(Moennig, 2000; Artois et al., 2002; OIE, 2002; Fritzemeier et al., 2000)
Airborne	+	-	(Elbers et al., 1999; OIE, 2002; Stegeman et al., 1997)
Other carriers (mechanical vectors)	+	-	(Liess, 1987)
Iatrogenic transmission	+	-	(Liess, 1987)
Artificial insemination	+	+	(De Smit et al., 1999; Elbers et al., 1999; Stegeman et al., 1997)
Vertical transmission	+	-	(Elbers et al., 1999; OIE, 2002)

Table 2.1 The transmission mechanisms for classic swine fever [CSF]

A similar body of knowledge exists for the chemical and biochemical hazards potentially released from carcasses during disposal activities (NIOSH, 2005; ATSDR, 2010). Information on hazardous agents characteristics, i.e. EAD agent and otherwise, is common to all outbreak stages. Therefore, it is available to support intervention strategies directed across all three phases of an EAD outbreak.

2.1.2 Studies on past EAD outbreaks

Following an outbreak, governments and international organisations report on the analysis of these events. These documents describe in detail the events known to have taken place during the progression of the outbreak with an inquiry into the causes and decisions made to resolve the incident. Epidemiological reports on past outbreaks include information on the pathways leading to EAD introduction for the pre-outbreak phase, alongside information on the progression of the outbreak during the outbreak phase (OIE 2010). In addition, governments may sometimes develop specific documents that report the environmental impacts relating to the disposal of the carcasses during post-outbreak phase (Environment Agency, 2001).

An analysis of these documents exposes a discrepancy in quality and quantity of information available for each of the three outbreak phases. Typically, epidemiological reports identify the progression of the EAD agent during the development of the outbreak (t_0-t_2) phase (Sharpe et al., 2001; Defra, 2007c; OIE, 2010). The UK develops reports that provide a particularly accurate recount of transmission events involved in the progression and resolution of the outbreak (Sharpe et al., 2001; Defra, 2007c; Anderson, 2008; Fritzemeier et al., 2000). Alongside official reports, a number of studies are available in research papers that focus on the identification of all infected premises and the chronological development of a specific outbreak (Cottam et al., 2008b; Green et al., 2006; Fèvre et al., 2006; Elbers et al., 1999; Stegeman et al., 1997; Haydon et al., 1997). Therefore, there is a sound knowledge base on the progression of an outbreak following the infection of the first premises, i.e. the nature of the source-pathway-receptor relationship contributing to disease spread and the geographical dispersion of an EAD during an outbreak.

In contrast for the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases, the published data that informs on the source-pathway-receptor relationship is limited. Information regarding the behaviour of the system during the pre-outbreak (pre t_0) phase is present in the same epidemiological reports that record the spread of the EAD during the outbreak phase (OIE, 2010). These reports include an analysis of pathways of exposure responsible for EAD introduction. However, whilst the majority of these reports are successful in identifying the first infected premises as well as the outbreaks' chronological progression, only a small portion are successful in presenting a conclusive hypothesis for the pathways of introduction. For example, from the epidemiological reports published between 2008 and 2010 regarding CSF and FMD outbreaks, only 30% advance a conclusive hypothesis for the source and pathway of exposure responsible for the infection of the first premises (OIE, 2010). Furthermore, reports developed and commissioned by Defra at times fail to specify the introduction pathways associated with the outbreak (Gibbens et al., 2000; Scudamore, 2002; Defra, 2007b). The existing reports address the pathways of exposure responsible for the introduction of EAD. However, as most reports are inconclusive, uncertainty remains on the actual pathways of introduction. Thus, it limits the insights produced on the source-pathway-receptor relationship and on UK's vulnerability to EAD introduction through the same pathways introduction.

Information on the system behaviour associated with the post-outbreak (post t_2) phase relies on monitoring the activities performed during the disposal of carcasses. Research evidence is limited for this phase. The option to cull all infected and potentially infect animals is available for dealing with any EAD. However, reports that review the activities associated with the disposal of carcasses are limited to those produced during the FMD outbreak of 2001 (Scottish Executive, 2002; Lowles et al., 2002; Environment Agency, 2001; Scottish Executive, 2001), published work on carcass disposal through composting and burial of carcasses (Glanville, 2000; Glanville et al., 2006; Glanville et al., 2008) and a study on the disposal of fallen stock (Ritter and Chirnside, 1995). Furthermore, the available information on the environmental impact caused by the disposal of carcasses is incomplete, as the existing reports on the environmental impact address a fraction of environmental release sources associated with carcass disposal activities. Therefore, there are a number of activities associated with the disposal of carcasses, such as culling on farm, whose environmental impact is unknown. It is clear that the information available from past events is insufficient to establish a link between the sources (disposal activities) and pathways of exposure, and the environmental impact and UK's vulnerability to a resurgence of the EAD. Therefore, data on the source-pathway-receptor relationship associated with the post-outbreak (post t_2) phase is limited.

2.1.3 Predictive modelling

Where evidence is available, predictive modelling can be used to estimate the outcome of an event (Singer et al., 2011). Here we analyse the capacity of existing predictive models to generate insights on system behaviour, i.e. the source-pathway-receptor relationship, across all three phases of an outbreak (Taylor, 2003). These models use data available from research on EAD agent transmission characteristics and documents recording past events. From this information, the models calculate the likelihood and/or impact of exposure (Taylor, 2003; Singer et al., 2011). Predictive models vary in complexity from highly complex computer based models to simpler *expert-based* ones (Taylor, 2003; Singer et al., 2011; Murray, 2002). Despite the differences in modelling approach, all models aim to provide insights on the activities posing influence in the source-pathway-receptor relationship. As a result, predictive models are instrumental in identifying which pathways and transmission modes pose a greater threat for exposure to an EAD agent. This information presents valuable insights to support strategies to control exposure of livestock to EAD. Predictive modelling applied to study EAD outbreaks is associated with risk assessment (RA). This results from their capacity to assist in identifying the most influential factors and weaker controls to transmission within the phases of an outbreak (Singer et al., 2011). Table 2.2 contains a description of terms and concepts used to describe and classify these models.

This review of predictive models applied in RA to study EAD outbreaks focuses on their capacity to generate insight on the system behaviour for each of the three phases of an EAD outbreak. A predictive model that contributes to the understanding of system behaviour involves understanding the full extent of the source-pathway-receptor relationship and therefore considering all available pathways of exposure and control in place. Under this definition of system behaviour, the achievements of predictive modelling and of RA development differ between those that focus on the outbreak phase and those that focus on the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases.

Term	Meaning	References
System	The source-pathway-receptor relationship	(Pearce and Merletti, 2006; Borrett and Patten, 2003)
System behaviour	The interactive relationship between an EAD agent and the source-pathway-receptor	(Pearce and Merletti, 2006)
Pathways system	All available pathways of exposure that form links between source and receptor for a specific pathogenic agent	
Predictive modelling	Studies developed to predict the outcome of one or multiple events. These model may be computer-based or expert-based	(Taylor, 2003; de Jong, 1995)
Expert based model	Modelling technique relying on the opinion of experts to predict the system's behaviour	(Singer et al., 2011)
Scenario-based model	Computer based model focussing on one or multiple pathways of exposure. These models use a binomial or an event tree based model to estimate the likelihood or quantity of the agent exposed through a pathway	(Vose, 2008; Singer et al., 2011; Murray, 2002)
Import risk assessment (IRA)	Predictive study targeting transmission during the pre-outbreak phase or pre t_0 phase	(Singer et al., 2011)
Disease spread model	Predictive study targeting transmission during the outbreak phase or t_{0-2} phase	(Dubé et al., 2007)
Carcass disposal assessment (CDA)	Predictive study targeting the impact of carcass disposal during the post-outbreak phase or post t_2 phase	(Pollard et al., 2008a)
Risk factor	Any form of EAD transmission, e.g. livestock, meat produce, fomites, vectors, other host)	(Horst et al, 1996, Defra 2011a)
Hazardous agent	Substance or biological entity liable to cause harm to a receptor: including EAD agents and other chemical, biochemical and biologic agents	(Haas et al., 1999; Vose, 2008; Taylor, 2003)
Barrier	Any obstacle reducing the chances of disease transmission, these may be physical and biological barriers and activities performed	(Murray, 2002; Morley, 1993)
Bottom-up model	Modelling technique, based on the description of the system where system behaviour and pathways systems emerges for a series of rules used to define the EAD agent transmission characteristic	(Murthy and Krishnamurthy, 2009; Dangerfield and Morris, 1992; Freeze et al., 2005)
Top-down model	Modelling technique, where the assessor or experts based on their perception of system behaviour, define the pathway(s) or pathways system used to estimate the impact of exposure	(Murthy and Krishnamurthy, 2009; Dangerfield and Morris, 1992; Freeze et al., 2005)

Table 2.2 Review of terms and concepts used for describing predictive models

2.1.4 Predictive modelling applied to the outbreak (t_0-t_2) phase

Multiple predictive modelling tools have been developed to estimate the outcome of the outbreaks and spread of the disease during the outbreak (t_0-t_2) phase. These include *expert-based* qualitative assessments (Wieland et al., 2011; Hartley, 2010) and *scenario-based* qualitative assessments focussing on one activity or agent transmission characteristic (Gloster et al., 2010; Donaldson and Alexandersen, 2002; Donaldson et al., 1982). The development of predictive tools to study the progression of the outbreak during this phase recognises the need to apply a systemic approach that develops a complete understanding of the events driving exposure. Such approach focuses on assessing all risk factors influencing transmission, all pathways of exposure and controls preventing it. Specific models applied to analyse the outbreak (t_0-t_2) phase generate a comprehensive understanding of system behaviour and estimate the EAD spread during an outbreak. These are comprehensive disease spread models and the leading examples are the North American Animal Disease Spread Model, the AusSpread and the Inter-Spread RAF (Harvey et al., 2007; Dubé et al., 2007; Garner and Beckett, 2005; Mintiens et al., 2003).

Comprehensive disease spread models are detailed models, which consider multiple factors influencing disease spread. These factors include manmade activities and trade that promotes the inter-farm contact, the disease agent characteristics and the geographical concentration of farms. These are developed to include wind speed and wind direction to estimate the airborne transmission of the EAD agents (Harvey et al., 2007; Dubé et al., 2007; Garner and Beckett, 2005; Mintiens et al., 2003). These models also account for the regulations in place that reduce the likelihood of inter-farm transmission.

Model development follows a bottom-up (BU) approach (Murthy and Krishnamurthy, 2009; Dangerfield and Morris, 1992). A BU approach to model development focuses on establishing a thorough description of the system. This focuses on identifying all components playing a role in EAD transmission and the characteristics of their behaviour. These components include farms, manmade activities and the regulations controlling them. The interactive behaviour of these components and the EAD agent is characterised by a series of local governing rules that define the interactions between components in the system (Murthy and Krishnamurthy, 2009). These rules include farm descriptions, such as farm types, size and the geographical dispersion (Dubé et al., 2007; Ward et al., 2009). Information regarding manmade activities promoting inter-farm contacts includes the frequency of movement between farms and movement types (Garner and Beckett, 2005). Lastly, the EAD agent is characterised by its ability to remain viable when outside a host by conveying its transmission characteristics, i.e. direct spread and possible airborne and vector based transmission (Harvey et al., 2007; Garner and Beckett, 2005; Donaldson et al., 1982).

Computer models estimate the behaviour of the system emerging from these local rules. This approach to model development is not unique to these disease spread models. In fact, it is available in other domains such as engineering and finance (Freeze et al., 2005; Huhn et al., 2011; Takahashi and Terano, 2006). Models developed through this approach, where the focus is on system behaviour are defined as systemic models. Systemic disease spread models structure characteristics that provide opportunities to generate insights to a system's behaviour. These can prove useful in the support of intervention strategies (Garner and Beckett, 2005). These are:

- Develop a system characterisation that includes all factors and components influencing EAD transmission. This approach acknowledges the possible complexity associated with disease transmission, which may be difficult to perceive prior to the assessment (Morris, 1995; Pearce and Merletti, 2006). Thus, it removes prior judgements and bias based on the perceived likelihood from model development. This allows for the development of a model that is equally sensitive to factors perceived as high or low significance. This makes them an ideal tool to deal with a system where priorities are not easily identifiable. For example, long tail risks (H.M. Treasury, 2004).
- System behaviour emerges from the local governing rules, allowing identifying patterns of behaviour where they are difficult to predict. This quality of systemic models generates insight regarding how disease spread occurs (Murthy and Krishnamurthy, 2009; Pearce and Merletti, 2006).
- The development of sensitivity analyses to study system behaviour. Protocols for sensitivity analysis change the local governing rules to measure their effect on the system's behaviour. This establishes a link between a system component and the system's behaviour that identifies which components pose the greatest influence on disease spread. Furthermore, this allows testing intervention strategies targeting specific components generating insight on how best to control spread during an EAD outbreak (Murthy and Krishnamurthy, 2009; Carré and Singer, 2008).

Disease spread models as systemic models provide an understanding of the source-pathway-receptor relationship responsible for disease spread. These models provide an understanding of the mechanisms responsible for EAD transmission, generating insights on system behaviour. These insights support the development of effective policy interventions to control of future EAD outbreaks. The development of comprehensive disease spread models depends on the availability of data to characterise the system (input data) and for validation (Garner and Beckett, 2005). Such information is available for the outbreak (t_0-t_2) phase from studies on the transmission characteristics of EAD agents and studies from past EAD outbreaks.

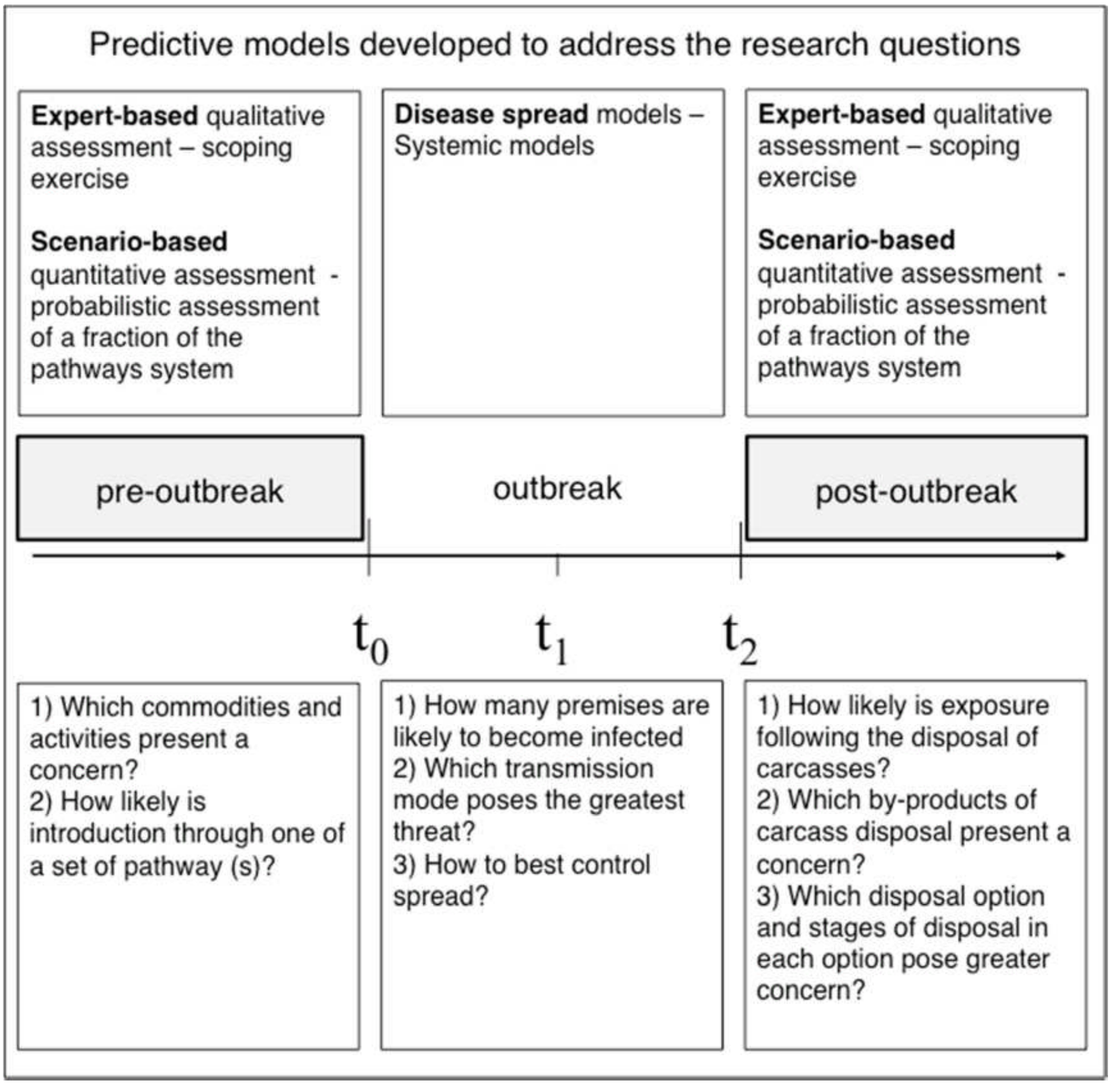

Figure 2.1 Enumeration of the predictive model used to generate insight on system behaviour for each outbreak phase and research questions answered by those models

2.1.5 Predictive modelling for the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases

The development of predictive models for the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases follows a different approach. No research evidence is published on the application of comprehensive models to study these two outbreak phases. However, there are mitigation strategies in place to control the introduction of EAD agents (Defra, 2011a). Similarly, Defra has developed a contingency plan for carcass disposal to prevent a resurgence of the EAD whilst minimising the environment and health impacts (Defra, 2009b). Development of these plans and control measures requires an understanding of the source-pathway-receptor relationship associated with each outbreak phase. Following is an analysis of the predictive models used to study these two outbreak phases (Figure 2.1). This review focuses on analysing the capacity of these predictive models to generate insights on the source-pathway-receptor relationship associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases. The review includes detailed descriptions of the methods used, as well as the scope associated with the models identified in the research literature. Predictive models developed for each of these two phases assess two systems with different configurations and behaviour. Therefore, this review analyses the models developed to assess each phase separately. However, there are similarities in the modelling approaches, which became apparent during these analyses. Therefore, a final analysis on the efficacy of these models to produce insights on system behaviour and information to support the reduction of UK's vulnerability to an EAD follows this methodological review.

2.2 Predictive models applied in the pre-outbreak (pre-t_0) phase

EAD transmission during the pre-outbreak (pre t_0) phase occurs within a system that includes complex interactions between multiple components. The system displays a network like configuration, where the interaction between components creates a large number of pathways available for EAD introduction. For example, Figure 1.4 represents only a fraction of the entire system. These pathways result from the interaction between two or more components and the EAD agent describing the sequence of events leading to the exposure of livestock to an EAD (Defra, 2011a). The influence of the disease transmission characteristics is described in the list of risk factors considered for each disease (Horst et al., 1998, Defra, 2011a). The risk factors (Table 2.2) represent the forms of disease transmission, which include transmission through meat products, live animals, fomites (e.g. livestock lorries), vector based transmission or even airborne transmission of an EAD (Horst et al., 1998, Defra, 2011a). Therefore, the system assessed presents complexity generated from interactions between multiple system components and risk factors (Figure 1.4). This allows for a nonlinear behaviour, amplification loops and different permutations that increase the number of pathways of exposure considered within the system (Siu, 1994; Jordán and Scheuring, 2004; Mitchell, 2006).

The government's responsibility to implement controls and establish guidelines to prevent successful transmission extends to managing the pathways allowed within the network system (Defra, 2011a). Due to the size of the system associated with the pre-outbreak phase, the government maintains a system of controls consisting of regulatory bodies and enforcing agencies. These produce and enforce regulations that aim to detect and eliminate the disease agent before exposure to livestock animals. As a system of controls, the regulatory bodies and enforcement agencies are responsible for controlling all components within the system, i.e. the UK's livestock industry, on the border inspection posts, livestock trucks, laboratories, farms, wildlife, and slaughterhouses (Defra, 2011a). Each one is responsible for supervising and controlling activities associated with a specific section or node from the network. The design of the system of controls deliberately places the organisations and groups to create redundancy, so that along the pathways of exposure multiple successive chances of detection and elimination are established, i.e. barriers. This defines a multi-barrier system (Reason, 1997). The multi-barrier setting accounts for protection against potential failures in eliminating the disease agent, so that in the event that one of them fails, the subsequent barrier assures that the system is uncompromised (Reason, 1997; Pidgeon and O'Leary, 2000).

Predictive models applied to study the pre-outbreak phase focus on testing the efficacy of the multi-barrier system in preventing the introduction of an EAD into the UK (OIE, 2011c; Vose, 2008; Taylor, 2003; Murray, 2002). Predictive models associated with this outbreak phase are designated as import risk assessments (IRA) (Singer et al., 2011).

2.2.1 Expert-based qualitative risk assessment

Expert based qualitative assessments represent a type of predictive models used consistently by governments to develop IRA (Peeler et al., 2006). Governments adopt a qualitative template for routine assessments, e.g. UK, Australia and New Zealand (Defra, 2011c; Reed, 2009b; BioNZ, 2006). In the UK, Defra applies qualitative assessment methods following the notification of an animal disease outbreak in foreign countries, to assess the threat these pose to the UK (Defra, 2011c). The templates follow the principles of the OIE qualitative framework (OIE, 2011c) and provide estimations of the risk associated with imported commodities and other risk factors (Figure 1.4). Each assessment compiles information on the geography and extent of an outbreak, the species involved and characteristics of the infectious agent (Defra, 2011c; Sabirovic et al., 2005; Sabirovic and Hall, 2004). Expert-based qualitative assessments help to understand the threat posed by outbreaks in foreign countries by estimating the individual risks posed by importing individual commodities and movement of people (Defra, 2011c). Imported commodities and movements responsible for the introduction of EAD are described as risk factors (Horst et al., 1996). Summaries within these assessments classify risks factors according to a nominal scale that allows for comparisons between imported commodities to define priorities for intervention.

Negligible	So rare that it does not merit to be considered
Very low	Very rare but cannot be excluded
Low	Rare but does occur
Medium	Occurs regularly
High	Occurs very often
Very high	Events occur almost certainly

Figure 2.2 Nominal ranking scale used by Defra to assessment the risk posed by the importation of different commodities(t_0-t_2) (Defra, 2008a)**.**

The documents published in association with the RA are vague in their descriptions of the elicitation technique producing these results (Defra, 2011c). They state with certainty, that methods applied use, expert consensus to develop expert rationale; and classify the commodities according to the nominal scale (Defra, 2011c; BioNZ, 2006).

The categories considered in Defra's template are described in Figure 2.2. However, categories within the scale vary with the template adopted for the assessment (BioNZ, 2006). The expert-based qualitative assessments provide a description and a classification according to a nominal scale of the commodities and movement of goods presenting a threat to the UK (Figure 2.2). However, assessments do not consider specific pathways of exposure or mechanisms associated with the commodities assessed. Thus, expert based qualitative assessment do not inform on specific barriers and controls, to communicate the mechanisms involved in EAD transmission or describe the complexity of the system assessed.

A key characteristic of these models resides in the use of expert knowledge. The expectation is that these provide guidance where there is a shortage of reliable quantitative data (OIE, 2011c; Defra, 2011c; Taylor, 2003). However, this means assessments result exclusively from the experts' rationale, and are influenced by their preconceptions, assumptions and concerns (Cooke, 1994; Tversky and Kahneman, 1974). Thus, outputs produced reflect the level of information available to experts and their preconceptions of system behaviour, limiting the capacity of expert based models to generate new insights on EAD transmission and system behaviour.

This review of expert based system models reveals that these provide an analysis of the entire system, however they are limited in the capacity to analyse its complexity and the exposure pathways. Therefore, expert-based qualitative models fail to specify the mechanisms responsible for EAD transmission and fail to capture new insights on system behaviour. As a result, the outputs produced provide limited information to support improvements to UK's resilience to an EAD outbreak.

2.2.2 Expert-based quantitative risk assessment

Expert-based quantitative assessments improve the qualitative approach by adopting more complex elicitation techniques, which retrieve expert judgments as quantitative values (Horst et al., 1998; Horst et al., 1996; Nissen and Krieter, 2003; Gallagher et al., 2002). The conjoint analysis is an alternative elicitation technique, developed by the marketing industry to estimate consumer preferences (Horst et al., 1998; Horst et al., 1996; Nissen and Krieter, 2003; Gallagher et al., 2002). Horst et al. (1996) first applied the technique to identify the relative importance of imported commodities and other risk factors in the introduction of CSF into the Netherlands. The conjoint analysis applies an indirect elicitation process. It involves creating profiles, each composed of different groupings and ordering of risk factors. Experts compare the profiles in pairs and express their concerns in terms of relative likelihood or probability beliefs for each profile pair (Horst et al., 1996; Dalton et al., 2010). A statistical analysis sorts between the profile comparisons and provides a relative ranking of the estimated influence each risk factor has in the introduction of CSF. Supporters of the conjoint analysis defend that ranking of relative likelihoods (in pairs) is a more natural quantity to conceive for one who is not accustomed to the idea of probability (Dalton et al., 2010). Therefore, the expectance is an improved accuracy of the outputs (Horst et al., 1996; Dalton et al., 2010). However, with the caveat that this process is time consuming, thus confining studies to a limited number of risk factors.

Since then, this approach has been applied by Horst et al. (1998) to estimate the number of expected primary CSF, FMD and Newcastle disease outbreaks in a five years interval and by Nissen and Krieter (2003) to expand the list of risk factors assessed to consider those associated with the EAD introduction and spread. The UK’s approach to expert-based quantitative models, involved modelling of FMD introduction to Europe. However, the exact elicitation technique is not described (Gallagher et al., 2002). This work expands the list of risk factors to include tourists and emigrants, personally owned vehicles, natural spread. The model provides a number of outputs from the number of primary outbreaks expected per region in the EU for a five years interval and assesses the most likely source of these outbreaks and the risk factors involved in introduction to the UK (Gallagher et al., 2002).

The expert-based quantitative assessments published, develop an output that is comparable to that of expert-based qualitative assessments (Horst et al., 1996; Horst., et al., 1998; Gallagher et al., 2002; Nissen and Krieter, 2003). These models organise predefined lists of commodities according to their estimated influence in future EAD outbreaks (Horst et al. 1996). The difference between the expert based qualitative and quantitative models resides on the elicitation technique used and scale used to communicate the ranking of risk factors. Here, outputs are presented according to an estimated probability score, contrasting with the classification according to a nominal scale. Nonetheless, the quantitative approach also fails to describe and analyse specific pathways responsible for exposure or the complexity of the system assessed.

This review of expert based quantitative assessments reveals these provide an analysis of the entire system, however they are limited in the capacity to analyse its complexity and the exposure pathways. Therefore, expert-based quantitative models fail to specify the mechanisms responsible for EAD transmission and fail to capture new insights on system behaviour. As a result, the outputs produced provide limited information to support improvements to UK's resilience to an EAD outbreak.

2.2.3 Scenario-based quantitative risk assessments

Scenario based assessments use a different approach to developing IRA. These assessments focus on developing detailed analysis of the pathways of exposure associated with the exposure of livestock to an EAD (Vose, 2008; Peeler et al., 2006; Murray, 2002). These are applicable to the same risk factors considered in the expert based assessments. However, scenario-based models analyse in detailed the efficiency of the controls in place. The outputs of these assessments provide an estimation of the likelihood of failure to detect and eliminate the disease agent before exposure to livestock to an EAD (Morley, 1993).

Scenario based assessments apply modelling techniques which focus on the representation of the pathways of exposure. The models recreate in detail the sequences of events and failures in the controls in place, resulting in the release and exposure of the livestock population to an EAD (Vose, 2008; Murray, 2002). Descriptions of the methods for building scenario-based models are available in the published literature (OIE, 2011c; Vose, 2008; Murray, 2002). The assessments apply models rooted in the development binomial models. The binomial model quantifies the outcome of the pathways (Singer et al., 2011). Risk analysis selects the scenarios to assess based on the objectives of the assessment. For example, studies assessing the risk of importing FMD through the importation of live animals address different scenarios from those assessing imports of deboned beef (Yu et al., 1997; Martinez-Lopez et al., 2008). The definition of the scenario to assess influences the development of the binomial model.

The definition of a scenario and thus the development of the binomial model, considers three steps: (i) characterise the source, (ii) define barriers to transmission, and (iii) estimate exposure to receptors. The source considers the presence of a disease agent at the origin country and the quantity of commodities imported. The definition of source includes:

- the volume of imported goods, e.g. live animals, meat products or genetic material, and
- the likelihood of contamination estimated by the true prevalence of the disease within the country of origin (Vose, 2008; Murray, 2002).

The definition of barriers includes any activity, control or even biological factors that contribute to reducing the likelihood of disease introduction.

- These barriers are present at source, during transit and at destination. Considering the importation of live animals, barriers included at source are animal selection and veterinary checks (Vose, 2008).
- A variety of barriers are considered within transit. Examples include the survival of animals from origin to destination for live animal transports or the possible inactivation of disease agents through the refrigeration of meat products (Yu et al., 1997; Sánchez-Vizcaíno et al., 2010).
- Barriers at the destination include the low likelihood of the exposure of livestock animal through contaminated meat produces and detection through veterinary controls, i.e. quarantine checks, and blood sampling (Hartnett et al., 2007; Bronsvoort et al., 2008).

The binomial model estimates the exposure to livestock. The model is a mathematical formula that considers all probabilistic "what if" estimates that condition the likelihood of exposure (Morley, 1993). The output of scenario-based models is a detailed analysis of the pathways of exposure, which results in an estimation of the likelihood of introducing the EAD agent.

In total, 13 quantitative end-point IRAs were identified in the research literature (De Vos et al., 2004; Morley, 1993; Yu et al., 1997; Martinez-Lopez et al., 2008; Sánchez-Vizcaíno et al., 2010; Hartnett et al., 2007; Bronsvoort et al., 2008; Hoar et al., 2004; Jones et al., 2004; Wahlstrom et al., 2002; Astudillo et al., 1997; Martínez-López et al., 2009; Weng et al., 2010). The histogram displayed in Figure 2.3 shows a comparison of assessments based on their scope.

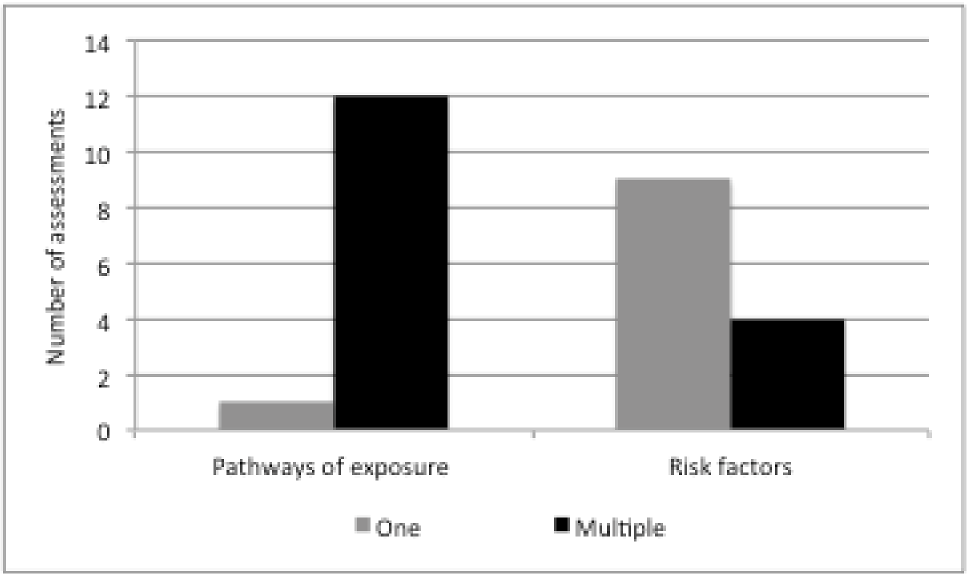

Figure 2.3 Analysis of the 13 scenario based assessment based on scope

[KEY] The analysis focuses the number of pathways of exposure (scenarios of introduction) and risk factors (commodity groups) assessed.

The majority of the assessments consider multiple pathways of exposure (Figure 2.3 - first column pair). However, one change to the sequence of events analysed generates a new scenario and a new pathway of exposure. Thus, although these assessments address multiple pathways, their scope is limited to variations of the same scenario (Vose, 2008; Murray, 2002). From the twelve assessments focusing on multiple pathways, eight analyse variations of the same scenario. For example, Jones et al. (2004) when the estimating risk of importing Brucellosis from EU countries, focuses specifically on two disease sources, Northern Ireland and the Republic of Ireland. Although the risk factor and the sequence of events remain unchanged, each new source represents a new scenario. The same is true for changes in receiving regions (Martinez-Lopez et al., 2008; Hoar et al., 2004), or changes in the series of barriers along the pathways, e.g. infection before or after vaccination (Weng et al., 2010). As a result, these scenario-based assessments produce analysis with a narrow scope, where focus is limited to the pathways of exposure associated to a single risk factor.

Four scenario-based assessments focus on multiple risk factors, all published since 2004 (Figure 2.3- second column pair). Within this group, three authors adopt the binomial model. Weng et al. (2010) presents one tree representing the legal movement of pets across the border, and a second tree for illegal movements. Similarly, Bronsvoort et al. (2005) considers risk factors in separate trees, i.e. the import of live breeding animals, semen, returning livestock trucks and legal and illegal meat imports. The work developed by De Vos et al. (2004) presents a model considering all risk factors within the same event-tree to assess scenarios combining multiple risk factors. This assessment considers the role played by exogenous and endogenous sources, e.g. wild boar population and laboratory releases. The modelling approach used is rooted in the same principles as conventional scenario-based models, however it analyses an increased number of risk factors and pathways of exposure. The development of scenarios based assessments focussing on multiple risk factors, suggests these develop comprehensive analyses of the source–pathway-receptor relationship. However, these models analyse one or a small number of pathways for each risk factor (De Vos et al., 2004; Bronsvoort et al., 2005; Weng et al., 2010). As a result, these models maintain a small scope, which focus on a small number of scenarios of EAD introduction, considering all pathways of exposure available in the system (Figure 1.4).

The remaining scenario-based assessment focussing on multiple risk factors, adopts a different modelling technique (Hartnett et al., 2007). This is an agent-based model and represents an alternative to conventional binomial models. It follows a systems approach to modelling the disease incursion. This approach focuses on representing the system as a network of connections, where pathways arise from a rules governing network behaviour (Murthy and Krishnamurthy, 2009; Newman, 2003). Hartnett et al. (2007) explores the concept of exogenous and endogenous pathways in a study dedicated to assess the influence of illegal meat imports in the introduction of FMD into the UK. It differs from the conventional IRA approach by describing the system, represented as a network, to simulate the events taking place within UK borders that are responsible for exposure of livestock to FMD. This study focuses on illegally introduced meat products (one risk factor), however once these are released into the country it acknowledges that exposure depends on a wider range of risk factors, such as wildlife population, swill feeding and humans as fomites (Hartnett et al., 2007). This approach presents the potential to develop a truly comprehensive analysis of the system associated with pre-outbreak (pre t_0) phase. However, as the assessment focuses on illegal imports of meat products alone, it fails to achieve this.

This review of the scenario-based models published reveals these develop analysis with a narrow scope, focussing on a small number of pathways. This results from the need for quantitative data to inform on the quantity of the EAD agent and on the barriers to transmission considered by the binomial model. Considerable effort is necessary to collect these data, making the development of such models time consuming (Taylor, 2003; Peeler et al., 2006; Singer et al., 2011). Furthermore, it compromises the development of assessments for pathways of exposure for which high quality data is unavailable (Taylor, 2003; Peeler et al., 2006). Thus, this characteristic of scenario-based models restricts their focus to one or a small number of risk factors and an equally reduced number of pathways of exposure. Whilst, these models produce a detailed assessment of the likelihood of EAD introduction, they analyse a fraction of the pathways of exposure available in the system (Figure 1.4). As a result, mechanisms of exposure identified as influential for a specific pathway may not correspond to a similar influence in system behaviour. Thus, the outputs produced provide limited information to support improvements to UK's resilience to an EAD outbreak.

2.2.4 Insights on system behaviour developed by the IRA

The IRA published to date to study can be defined into three categories base of the technique used to develop the predictive models (Table 2.3). Here, there is a clear distinction between the expert-based and scenario-based assessments. Expert-based models include expert-based qualitative and expert-based quantitative models. Scenario-based models include scenario-based quantitative assessment and an agent-based model. Table 2.3 describes the result of this analysis the focus on the assessments reviewed.

Expert-based assessments developed scoping exercises of the system. These develop an overview of the system, which sacrifices the level of detail with which pathways are described (Defra, 2011c; Sabirovic and Hall, 2004; Horst et al., 1998). Therefore, these assessments fail to specify the pathways and the mechanisms responsible for exposure (Table 2.3). Furthermore, prioritisation of risk factors results from the experts and assessors preconceptions of system behaviour. In doing so these models fail to analyse the system in sufficient detail as to provide new insights on the system behaviour or to identify clear solutions for policy interventions that to reduce significantly UK's vulnerability to EAD outbreaks.

	Analysis of the entire system	Pathways of exposure assessed in detail	Provides insights on S-P-R relationship
Expert-based qualitative assessment	**Yes**	**No**	**No**
Expert-based quantitative assessment	**Yes**	**No**	**No**
Scenario-based quantitative assessment	**No**	**Yes**	**No**

Table 2.3 Analysis of the IRA according to the scope of the assessments

[Key] S-P-R stands for source-pathway-receptor

The scenario-based assessments focus on assessing, in detail, specific pathways of introduction, however focusing on a small number of them (Table 2.3). However, their narrow scope means that insights of system behaviour result from incomplete analysis of the system. Thus, the priorities identified relate only to the pathways assessed and may not be significant to UK's vulnerability to EAD, providing little insight on the system behaviour.

The conclusion from this analysis is that the predictive models, whether expert-based and scenario-based assessments, produce incomplete analyses of the system. Expert-based models sacrifice detail by not describing mechanisms involved in exposure and in contrast, whilst scenario-based models favour detail sacrificing the relation between the pathways of exposure assessed and system behaviour. Therefore, all IRA published to date provide incomplete insights on system behaviour to support policy improvements to UK's resilience against an EAD.

2.3 Predictive models applied in the post-outbreak or post-t_2 phase

The post-outbreak phase considers a system that includes multiple environmental releases of hazardous agents (Figure 1.6). These releases are associated with the different activities associated with “stamping out” and “vaccinate to kill” policies (Pollard et al., 2008b). These include culling on farm, transporting carcass to the disposal system, processing the carcass and management of residual products from the processing of the carcass. The system involves all releases associated with all disposal options available for the disposal of carcasses (Defra, 2009b). This means a large number of exposure pathways are available.

It is the government’s responsibility to implement controls and establish guidelines to prevent the resurgence of the EAD following disposal activities and to minimise their environmental and health impacts (Marsland et al., 2003; Lowles et al., 2002; Pollard et al., 2008a; DH, 2001). Defra provides guidelines for disposal activities where these are necessary (Defra, 2009b). Moreover, it adopts exiting directives for the disposal options that have them. For example, the disposal of carcasses through fixed plant incineration (Defra, 2009c). Predictive models test the existing protocols and guidelines regarding their impact to the environment and on the health of livestock and human populations. The models associated with this outbreak phase are defined as carcass disposal assessments (CDA)

The majority of CDA are UK based in consequence to the BSE, FMD and HPAI outbreaks. These include CDA developed for the BSE crisis in the 1990s’ (Spouge and Comer, 1997b; Gale, 1998; Gale et al., 1998; Gale and Stanfield, 2001), the FMD crisis of 2001 (DH, 2001) and the HPAI international crisis (Pollard et al., 2008a). Curiously, each crisis is associated with a particular RA technique. The BSE crisis is associated with scenario-based quantitative assessments, FMD crisis with an expert-based qualitative assessment and the HPAI crisis with an expert-based semi-quantitative risk assessment. Therefore, the review will address the RA methods by analysing each of the pre-mentioned crises.

2.3.1 Scenario-based quantitative risk assessments

BSE is a prionic disease, associated to the cause of the Creutzfeldt Jakob Disease in humans (IFST, 2004; Brown, 2001). In contrast with the majority of the diseases included in the notifiable diseases list, which are caused by viruses, bacteria and parasites, BSE results from a mutated protein, the prion (IFST, 2004). These are highly resistant to inactivation, withstanding temperatures in the order of 600^{o}C, and surviving long periods in the soil (Brown and Gajdusek, 1991; Brown et al., 2004; Cooke and Shaw, 2007). The development of the CDA followed the identification of a probable link between CJD and BSE, therefore focussed mainly in the possible exposure of humans to prions (Smith and Bradley, 2003; Morley et al., 2003; Bradley and Wilesmith, 1993). The crisis lasted for more than a decade, whilst the number of animals “disposed of” remained below 200,000 (VLA, 2009). This allowed restricting the disposal options used to highly controlled ones, which in turn reduced the likelihood of a severe health impact resulting from the destruction of carcasses (Spouge and Comer, 1997b). Therefore, CDA of BSE focused on the disposal of possible infected livestock through rendering, incineration and landfill and the risk of environmental contamination and human exposure to BSE prions.

A review of all risk assessments developed during the BSE crisis is available in the work developed by Grist (2005). These predictive models represent the pathways of exposure using event-tree diagrams. Event tree diagrams represent binomial models, which are used to calculate the flow of the prions. Thus these provide an estimation of the environmental contamination and of subsequent exposures (Spouge and Comer, 1997b; Gale et al., 1998; Gale and Stanfield, 2001; Spouge and Comer, 1997d; Spouge and Comer, 1997c; Spouge and Comer, 1997a; Gale, 2005; Huntly et al., 2002; Cummins et al., 2002).

CDA develop through scenario based models use an event-tree to describe the exposure pathways from source to environmental release. Exposure is characterised by the infective dose 50 (ID50) load present at the end of each pathway. Through the pathways, sequential proportional reductions to the initial load of ID50 are estimated which correspond to the controls in place to mitigate transmission. Scenario-based quantitative assessments produce a dose-response model estimating the quantity of prions released into the environment and subsequently estimate the risks to the human population (Spouge and Comer, 1997b; Gale et al., 1998; Gale and Stanfield, 2001; Spouge and Comer, 1997d; Spouge and Comer, 1997c; Spouge and Comer, 1997a; Gale, 2005; Huntly et al., 2002; Cummins et al., 2002). CDA developed for BSE were marked by the assessments developed by the Der Nordske Veritas (DNV) and by Paul Gale (WRc NSF, Tilehurst). The aim of the DNV models was to determine whether the use of rendering, incineration and landfill for the disposal of BSE infected carcasses was safe for the UK human population. Thus, this assessment analyses multiple pathways of exposure associated with carcass processing activities, where the total ingestion of ID50s provides a measure of that risk to the English and Welsh populations (Spouge and Comer, 1997b). Contrastingly, the “Gale assessments” focus on the risk posed by one individual pathway (Grist, 2005). For example, the contamination of water discharged from the rendering process, the potential contamination of an aquifer and exposure to human through ingest of water from the aquifer (Gale et al., 1998).

Independently of the modelling technique used, all models developed for BSE are based on a similar modelling approach. Combined, these models analyse the exposure pathways associated with the processing stages of a small number of highly controlled disposal options. Therefore, considering the number of disposal options available (Pollard et al., 2008) and the multiple stages of disposal considered within each option, these models address a fraction of the release sources included in the system (Figure 1.6). The narrow scope of these assessments, results in a failure to assess the system of disposal options in its entirety. In short, these CDA provide an incomplete analysis of the source-pathway-receptor relationship, thus producing limited information to improve the existing protocol for safe disposal of carcasses.

2.3.2 Expert-based qualitative risk assessment

The Foot and Mouth crisis of 2001 was catastrophic. Overall, it involved the destruction of more than 6 million animals, including cattle, sheep, pigs and deer (Scudamore et al., 2002). At the height of the outbreak, the weekly disposal rate was over 600,000 animals, overcoming the available capacity for preferred disposal options. This resulted in the adoption of less contained methods of carcass disposal (Anderson, 2002; Scudamore et al., 2002). The department of health (DH, 2001) developed a qualitative assessment to evaluate the safety of the disposal options available to process the carcasses of infected animals. The assessment focused on the activities performed during the processing stage alone. The document published includes a description of the sequence of exercises performed during the elicitation. However, information is limited on the actual elicitation technique (DH, 2001). The model follows the conventional template for qualitative assessments, composed of hazard screening exercises and an exposure assessment for each disposal option (OIE, 2011c). The results presented for each disposal option are comprised of: (i) collection of the hazardous agents of concern selected from a list that included biological, chemical and biochemical agents, (ii) enumeration of exposure pathways deemed as influential, and (iii) ranking of the disposal options according to the estimated risk of exposure (DH, 2001).

This CDA focuses on the processing stage of five disposal options and considers a large number of hazardous agents, including pollutants and a range of pathogenic agents, exotic and not (DH, 2001). However, the model disregards the releases of hazards associated with activities taking place before and after processing of the carcasses. As a result, the model focuses on a fraction of the activities considered within the system. Furthermore, whilst it enumerates a small number of pathways of exposure, it fails to analyse in detail the events leading to exposure or the controls in place to prevent it. This CDA develops an incomplete analysis of the source-pathway receptor relationship and fails to identify the mechanisms responsible for exposure. Thus, the model produces limited information to improve the existing protocol for safe disposal of carcasses.

2.3.3 Expert-based semi-quantitative risk assessment

The semi-quantitative assessment provides a different approach to study the environmental impact caused by carcass disposal activities. Pollard et al. (2008a) published a model focussing on the disposal of carcasses that strikes a middle ground between expert-based qualitative and scenario-based quantitative assessments. This model develops the first comprehensive assessment of carcass disposal activities (Pollard et al., 2008a).

The scope of the assessment includes a wide range of disposal options including all activities performed during disposal of carcasses. For example, the model includes an analysis of the activities performed on premises. The potential impact of these activities is mentioned in the Drummond report, published before 2001 and their environmental impact was recorded during the 2001 FMD crisis (EA, 2001; Drummond, 1999). However, previous assessments failed to address it. The model also analyses the activities associated with transport and reception of carcass at the disposal site. The model represents these disposal activities through a disposal chain, normalising all disposal options into five stages. As the assessment focused on considering all environmental releases of hazardous agents that result from carcass disposal activities, a total 65 release sources were assessed (Pollard et al., 2008a). Modelling the environmental impact of carcass disposal was prioritised over the potential resurgence of the disease. Therefore, each release considered a large set of hazardous agents associated with environmental pollution alongside the HPAI virus.

The format of the assessment allows for the comparison between the different disposal options and the disposal activities within each disposal option. The disposal chain considers five independent stages, each representing a disposal activity and an environmental release of hazards. In each stage, 38 pathways of exposure represent the environment. The model includes a description of the pathways but not a graphical representation or consideration for the sequences of process composing them. Instead, expert knowledge was used to assess each pathway individually by using a ranking scale ranging from (0) for a non-existent pathway, and (1) to (4) from negligible to high risk. Thus, the outputs published are based on ranking scores that result from the aggregation the pathways scores. In doing so, it fails to identify the pathways of exposure that are influential during each disposal stage.

Pollard et al. (2008) produces an analysis of the entire system by considering all independent release sources considered within it. However, whilst the modelling approach is based on the assessment of the pathways of exposure available during each stage, the outputs produced fail to communicate it. Therefore, the model fails to produce a complete analysis of the source-pathway-receptor relationship and thus to identify the mechanism driving exposure. As a result, this assessment produces limited information to support policy interventions and improve the existing protocol for safe disposal of carcasses.

2.3.4 Insights on system behaviour developed by the CDA

This review defines the predictive models used in the post-outbreak phase or CDA into three categories. These categories enclose all RA methods applied so far to develop insight on the mechanisms responsible for the resurgence of an EAD and the impact on the environment and health for the disposal of carcasses. The outputs produced are in line with the research needs present at the time of their development. However, these CDA generate incomplete insights on system behaviour and on the mechanisms responsible for transmission. Thus, providing limited information to support policy interventions and that improve protection against the resurgence of an EAD following disposal of animal carcasses. Table 2.4 describes the results of this analysis the focus on the assessments reviewed.

	Analysis of the entire system	Pathways of exposure assessed in detail	Provides insights on S-P-R relationship
Scenario-based quantitative assessment	**No**	**Yes**	**No**
Expert-based qualitative assessment	**No**	**No**	**No**
Expert-based semi-quantitative assessment	**Yes**	**No**	**No**

Table 2.4 Analysis of the CDA according to the scope of the assessments

[Key] S-P-R stands for source-pathway-receptor

The scenario-based quantitative assessments produced a detailed analysis of the pathways exposing humans to BSE. These assessments provide an analysis of the barriers to transmission present in these pathways. Therefore, they present the potential to identify those barriers where failure results in a significant increase in the likelihood of exposure to BSE (Table 2.4). However, their focus is limited to the processing of carcasses through incineration, rendering and disposal in landfill (Spouge and Comer, 1997d; Spouge and Comer, 1997c; Spouge and Comer, 1997a). Moreover, the assessments focus on BSE and ignore all by-products resulting from the disposal of carcasses. In short, these assessments fail to develop a comprehensive analysis of the disposal options available in the system. Thus, scenario-based assessments produce limited insights on the source-pathway-receptor relationship and limited information to improve the disposal hierarchy.

The expert-based qualitative assessment developed for FMD presents an incomplete analysis of the system, which results from focusing on the processing stages for five disposal options (Table 2.4). Furthermore, it fails to describe the pathways causing exposure of livestock and human population to hazardous agents. Thus, its output provides limited insights on the source-pathway-receptor relationship and limited information to improve the disposal hierarchy.

The expert-based semi-quantitative model provides an assessment of all environmental releases from carcass disposal considered in the system (Table 2.4). Furthermore, the model analyses an extensive number of hazardous agents, which include EAD and by-products of carcass disposal activities (chemical, biological and biochemical) (Pollard et al., 2008). However, its output does not disclose the pathways responsible for exposure. As a result, the model does not specify the mechanisms involved in environment contamination and exposure of livestock and humans to hazardous agents. Therefore, this assessment produces limited insights on the source-pathway-receptor relationship and limited information to improve the disposal hierarchy.

The conclusion from this analysis is that the predictive models applied to the post-outbreak (post t_2) phase, whether expert-based and scenario-based produce incomplete analyses of the system. The expert-based semi-quantitative model sacrifices detail by not describing mechanisms involved in exposure and in contrast, scenario-based models favour the detail sacrificing a comprehensive analysis of all source of hazardous agents included in the system (Table 2.4). Therefore, all CDA published to date provide incomplete insights on system behaviour to support policy improvements to the disposal options and the safety of the activities performed during the disposal of carcasses.

2.4 Insights produced on system behaviour for the pre and post outbreak phase

This review analyses the predictive models developed to study the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases. The review focussed on the models individual capacity to provide insights on the source-pathway-receptor relationship and their capacity to develop information to support policy intervention that reduce significantly UK's vulnerability to EAD.

The predictive models revised produced limited insights on system behaviour. This is an expected conclusion as generating such knowledge is outside the scope of these models (Section 2.2 and 2.3). Specifically, these models present a trend in their failure to produce insight on system behaviour (Table 2.3 and Table 2.4). The predictive models developed for both the pre-outbreak and post-outbreak phases demonstrate the following trend.

- Expert-based assessments consider the full-scope of the system, however fail to analyse the pathways and the mechanisms responsible for exposure to an EAD (Table 2.3 and Table 2.4). Consequentially, expert-based models fail to establish a link between the pathway and barriers to transmission, and the system's behaviour. Therefore, they fail to produce significant insights to support improvements to the system's behaviour.
- Scenario-based models analyse exposure in detail by assessing specific pathways and the barriers composing them. However, these models focus on one or a small fraction of the pathways available in system (Table 2.3 and Table 2.4). As a result, the barriers where failure significantly increases the likelihood of exposure through the assessed pathway may not represent a significant increase to UK's vulnerability to an EAD. Consequentially, scenario-based models also fail to establish a link between the barriers considered in the pathways assessed and the system's behaviour.

This trend agrees with findings from previous reviews of predictive models used to study animal health related issues (Taylor, 2003; Peeler et al., 2006; Singer et al., 2011). These reviews suggest that expert-based qualitative models produce a global analysis of the system. In contrast, scenario-based quantitative models produce a local analysis of the system by focussing on specific pathways of exposure (Taylor, 2003; Peeler et al., 2006). Thus, these produce differing perspectives on the causes of exposure, a global and a local perspective.

In addition, this review reveals a common approach to model development - with the exception of the agent-based model developed to study the illegal introduction of meat products (Hartnett et al., 2007). All models follow a top-down approach to model development. This is the approach conventionally used to develop risk models (Dangerfield and Morris, 1992), including those applied to study EAD transmission (Vose, 2008; Defra, 2011c; Murray, 2002). However, this approach limits the models capacity to develop insight on system behaviour. In conventional "*top-down approaches, end-point consequences are postulated and then the mechanisms by which these states may be reached are considered*" (Freeze et al., 2005). This means that this approach to model development depends on a prior understanding of the system's behaviour. Therefore, a limited understanding of its behaviour influences the quality of the outputs produced.

Limited understanding of system behaviour influences both expert-based and scenario-based models. Expert-based qualitative models rely on the expert's preconceptions of system behaviour to develop the rankings produced (Defra, 2011c). Therefore, these models are unable to produce new insight on system behaviour. Scenario-based assessments "*adopt certain characteristics of event tree analysis, but systematically* *limit the number of (...) combinations*" (Freeze et al., 2005). This means selecting a fraction of the pathways available in pathways system (Vose, 2008; Murray, 2002), narrowing the focus of the assessments and thus failing to ensure a comprehensive analysis of the system. Furthermore, the risk assessor selects which pathways of exposure to consider prior to the assessment (Vose, 2008; Murray, 2002), suggesting that preconceptions of system behaviour influence pathway selection and the output produced. Consequentially, models developed by a top-down approach are limited from the start in their capacity to generate new insights on system behaviour and to inform strategies to reduce vulnerability to EAD.

The collective review of IRA and CDA reveals that the predictive models used to study the pre-outbreak and post-outbreak phases were destined to fail at the task of generating new insights on system behaviour. The scope of these assessments is inadequate to develop that insight and the model development approach limits the capacity to generate new insights on system behaviour.

2.5 The collective insight of predictive models on system behaviour

Taylor (2003) and Peeler et al. (2006) suggest it is possible to overcome the individual limitations of the analysis produced by expert-based and scenario-based assessments. The solution relies on the collective insight produced by the predictive models. Therefore, combining the global perspective of expert-based models and the local perspective of scenario-based models, one can produce a comprehensive analysis of the system (Taylor, 2003; Peeler et al., 2006).

This approach assumes that the insights gained through the application of expert-based and scenario-based models are complementary. Therefore this approach is defined here as the "complementary approach" to produce comprehensive analysis of a system. It entails expert-based assessments to screen the system at a global level and define priorities that need addressing. The scenario-based assessments investigate those priorities, generating knowledge at a local level. This second assessment tier increases the level of detail gained regarding the influential pathways of exposure (Taylor, 2003; Peeler et al., 2006). Thus, applying the complementary approach to the pre-outbreak and post-outbreak phases may expose the source-pathway-receptor relationship, however scenario-based assessments study only the most influential pathways of exposure.

For the IRA and CDA analysed in the review we can state that complementary approach is not applicable for the post-outbreak phase, as the scenario-based model predates the expert-based ones. Therefore, these models fall outside the paradigm of the complementary approach. In contrast, it is applicable to the pre-outbreak phase.

The complementary approach merits consideration as it states a logical sequence of analysis that can provide for a deeper understanding of the system behaviour and its vulnerabilities. However, the approach presents flaws in its logic (Zio, 2009), which result from the top-down approach used to develop the predictive models. The approach supports its argument on the capacity of expert based assessment to provide an accurate analysis of the high-level priorities at a global level. Thus, it assumes that the available knowledge and expert's opinions are sufficient to provide a correct analysis of system behaviour. However, if this is not the case, and expert-based models fail to develop an accurate assessment, then the priorities developed may not reflect those of the system. As a result, analyses of the system based on such an approach may overlook important risk factors of disease transmission or highlight less influential ones.

The misleading priorities trickled down when used to define the scope of scenario-based models, thus overlooking the pathways of exposure associated with those overlooked risk factors. As result, the complementary approach can produce incomplete or inaccurate insights on system behaviour and priorities.

The complementary approach suggests that the individual limitation of the expert-based and scenario-based models can be overcome by using their collective knowledge to inform on system behaviour (Taylor, 2003; Peeler et al., 2006). However, the flaws in logic presented above allow for the argument that as source of information, it may not be reliable with a significant risk of producing misleading results. Thus, priorities defined using this approach may overlook significant activities and controls where improvement can significantly reduce UK's vulnerability to EAD.

This review of predictive model states that their use to overcome the limitations of the available data has not been entirely successful. IRA and CDA, used individually or combined produced incomplete analysis of the system and do not allow to identify, with authority, vulnerabilities in the system. Thus, uncertainty regarding the system behaviour during the pre-outbreak and post-outbreak phases of an EAD outbreak remains (Section 2.1.2).

2.6 Research opportunities associated with the pre-outbreak and post-outbreak phases

This review of the documents associated with the pre-outbreak and post-outbreak phases reveals an insufficient volume of information to produce insight on system behaviour. It results from the limited information developed through the analysis of past outbreaks (Section 2.1.2) and the production of predictive models that are inadequate to produce a comprehensive understanding of the system and its behaviour (Sections 2.4 and 2.5). Consequentially, there are knowledge gaps in the understanding of the mechanisms responsible for exposure associated with both pre-outbreak (pre t_0) and post-outbreak (post t_2) phases.

For the pre-outbreak (pre t_0) phase, the information available is insufficient to detect and identify all available pathways of exposure. For example, the risk pathways and countermeasures report, prepared by Defra (2011a) reveals the concerns regarding a particular type of pathways. Defra suggest investigating the "*risks from low/medium probability risk pathways (...) to identify and assess potential high impact scenarios (if a sequence of low probability events occur), taking into account current levels of risk management*". These sequences of low probability events (LPE) present an unknown level of threat, although such pathways have been suggested as a possible cause for past EAD outbreak in the UK (Gibbens et al., 2000; Sharpe et al., 2001; Defra, 2007c; Scudamore, 2002). Thus, these expose a gap in the understanding of the system and its behaviour.

For the post-outbreak (post t_2) phase, the information available is insufficient to evaluate all release sources associated with carcass disposal activities. The data published on the risk of EAD transmission associated with the disposal of carcasses fails to address the influence of activities performed prior to carcass processing on the overall risk of exposure posed to humans and livestock, e.g. culling on farm and transporting of carcasses to the disposal site, and on solutions to minimise that exposure. However, a report on the environmental impact of the 2001 FMD crises, identifies 3 of the 4 class four incidents to be associated with activities performed on farm (Environment Agency, 2001). Thus, the lack of information associated with such carcass disposal activities exposes a gap in the understanding of the system and its behaviour.

2.7 Furthering understanding of system behaviour for an outbreak

Efficient decision-making depends on the quality and quantity of the information available (OIE, 2011c). These information gaps present a discrepancy on the insights to systemic behaviour across the three outbreak phases. Therefore, it is logical to conclude that decision making for policy interventions associated with the outbreak phase (t_0, t_2) is privileged in comparison to the remaining two phases. This highlights the need to strengthen the current level of information associated with EAD transmission in the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases. Achieving this involves a conjoint effort to improve documentation on past outbreaks and improving predictive models to provide comprehensive analyses of the two systems. Efforts to improve the records of pathways of exposure associated with EAD outbreaks involve a long-term commitment to detect and record the pathways of introduction in future EAD outbreaks. This presents the most accurate source of information but it may take time before it proves fruitful.

Whilst the information available through recording the EAD outbreaks remains insufficient to inform on system behaviour for the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases, systemic predictive models can present an alternative solution (Section 2.1.3).

Systemic models focus on developing a comprehensive analysis of all pathways of exposure included in the system. However, they require extensive data to characterise the behaviour of the components in the system. The conventional source of information is the data published on the EAD transmission characteristics and information collected from past events. For example, disease spread models find support in the data collected from previous EAD outbreaks to characterise the system components behaviour (Garner and Beckett, 2005; Donaldson et al., 1982; Kiss et al., 2006). Therefore, the scarcity of data associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases can compromise the development of systemic predictive models. Here, expert knowledge can provide an alternative source of information (OIE, 2011c). This is an established source of information, used to generate information on systems where data in the research literature for characterisation is limited. There are challenges to the development of an expert-based systemic model associated with managing the experts and ensuring high quality data, e.g. managing expert biases (Cooke, 1994; Tversky and Kahneman, 1974). However, it does provide the opportunity to develop models that are based on the most current data therefore, providing the most up to date insights on system behaviour.

This review describes a need to improve the understanding of disease transmission during the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases of an EAD outbreak. Improvements involve strengthening the information sources currently available to improve control and reduce UK's vulnerability to EAD. Future work is likely to require an improvement in the capacity to record the trajectory and causes of future EAD outbreaks. This information will provide an accurate portrayal of system behaviour and of the mechanisms responsible for exposure of livestock to EAD. Currently that information is not available with sufficient quantity and quality to provide the necessary insight to support decision-making. Therefore, an immediate solution is in the development of systemic models. These are predictive models focussing on generating comprehensive analyses of the system. Thus, these models may provide insights to support decision-making that improves protection and reduces UK's vulnerability to EAD.

2.8 Conclusions

This review explored the methods by which information is collected and analysed to support the decision-making process and the development of strategies to control EAD outbreaks. The review resulted in the acknowledgement that EAD outbreaks incorporate three phases of disease transmission, with each phase presenting a different behaviour and posing a different impact associated with EAD exposure (Section 1.2). Furthermore, each outbreak phase corresponds to specific configuration of the system, requiring specific information to inform on the causes and impact of exposure. All phases play an important role in the progression of the EAD outbreak, which highlights the need to control them. The development of this review demonstrates the following insights:

1. From the perspective of a policy maker, an EAD outbreak considers three phases. The outbreak progresses through the pre-outbreak (pre-t_0) phase, the outbreak (t_0-t_2) phase and the post-outbreak (post-t_2) phase. Each phase presents a unique behaviour in transmission of an EAD. Therefore, specific solutions for control of EAD transmission are necessary for each phase of an EAD outbreak.
2. The information available to inform on the system behaviour is not consistent for all phases of an EAD outbreak. The information available to inform decisions for the pre-outbreak (pre-t_0) and post-outbreak (post-t_2) phases is limited. This creates knowledge gaps, as expressed by the LPE for the pre-

outbreak (pre-t_0) phase, and by uncertainty regarding the environmental and health impact posed by culling activities performed prior to carcass processing for the post-outbreak (post-t_2) phase.

3. Improving the information on the pre-outbreak and post-outbreak phases is likely to improve the capacity to intervene in these systems, increasing UK's overall resilience to EAD outbreaks.
4. Considering the options available to improve the information on the pre-outbreak (pre-t_0) and post-outbreak (post-t_2) phases, the immediate solution lies in the development of systemic models focussing on generating insight on system behaviour.
5. The data currently available in the research literature are insufficient for the development and use as input in a systemic model. However, expert knowledge provides an established source of information that can help overcome the scarcity of data associated with the pre-outbreak and post-outbreak phases.

3 RESEARCH OBJECTIVES

A review of the research to date shows that examples of systemic approaches to modelling the transmission of EAD and its exposure to livestock are associated with the outbreak (t_0-t_2) phase of an EAD outbreak. The systemic models, by presenting a comprehensive analysis of the source-pathway-receptor relationship, which develops information on the mechanism of exposure and system behaviour, present information to support decisions that aim to optimise EAD control within this outbreak phase. The review of research to date also demonstrates that there is limited information on the source-pathway-receptor relationship associated with the pre-outbreak (pre-t_0) and the post-outbreak (post-t_2) phases. Furthermore, it reveals that the predictive models applied to these stages develop partial analysis of the pathways system, resulting in the failure to identify all drivers of risk associated with these systems. This review suggests that the development of expert-based systemic models may produce the information needed to overcome the scarcity of information associated with those two phases that limits the understanding of system behaviour.

Based on the arguments stated in the literature review, the work developed and presented in this thesis focuses on the following research objectives:

1. The experimental development of systemic models to study the behaviour and risk drivers associated with the pre-outbreak (Pre-t_0) and post outbreak (Post-t_2) phases. This involves developing, for each stage, a model that considers the specific source-pathway-receptor relationship, and respecting the rules for developing systemic models (Section 2.1.4).
2. Identify for the pre-outbreak (pre-t_0) and the post-outbreak (post-t_2) phases, system vulnerabilities where intervention is likely to reduce significantly system

vulnerability to exposure of receptors to an EAD, and provide insights on the behaviour of the system and how best to improve its resilience.

3. Analyse the performance of the systemic models, based on the outputs produced in comparison with those produced by the assessments included in literature review and their capacity to inform on the research opportunities identified.

Figure 3.1 describes the outline of the thesis from Chapter 4 to 11. The work is presented in the order by which it was undertaken, as opposed to following the normal development of an outbreak. This resulted in the systemic model developed for the post-outbreak (Post-t2) phase being presented in Chapter 4 and 5, followed by the pre-outbreak (Pre-t0) phase, in Chapter 6 to 10, and discussion Chapter 11. Presenting the work in this order allowed for including in the narrative the lessons learned from a first application to study exposure associated with carcass disposal activities and their contribution to improve a second application to study the introduction of EAD into a disease free country (the UK).

Figure 3.1 Outline of the thesis

[Key] The figure displays the two planned experiments – post outbreak (post t2 - green) and pre-outbreak (pre t0 - blue) phase and the discussion (red). The numbers identify the chapters where each subject is addressed

PART 1 – SYSTEMIC ANALYSIS OF THE POST OUTBREAK (POST t_2) PHASE

Part 1 addresses the experimental development of an expert based systemic model to study the environmental release and possible exposure of receptors resulting from the disposal of animal carcasses during the resolution phase of an EAD outbreak. The model aims to assess all environment release sources and pathways of exposure associated with the options available for carcass disposal to the government for managing the outbreak. This project follows the need expressed by the Defra to appraise the options available for the disposal of animal carcass to support policy decisions on EAD outbreaks, specifically to "*establish (...) a transparent and logical methodology, which formed the basis of an effective decision support tool*". The expert-based systemic model aims to improve the existing understanding on the pathways of exposure and through it presenting the opportunities for improving protection against the resurgence of an EAD or harm posed to the human and animal population from the agents released during disposal activities.

Model development adopts a similar approach to that developed by Pollard et al. (2008) to study the environmental and receptor exposure to hazardous agent associated with HAPI infected carcasses (Chapter 4). This systemic model expands the application of the model to consider a wider range of disposal option and disease agents. This is followed by an extensive analysis of the output, resulting in the development of a comprehensive analysis of the system. This experiment includes a second model, developed to address the analytical limitations identified in the first model (Chapter 5). The combined output of both models produces a comprehensive analysis of the system, generating insight on its behaviour and on the drivers of exposure to EAD. A summary of the findings produced by the research presented in Part 1 is presented in Section 5.5

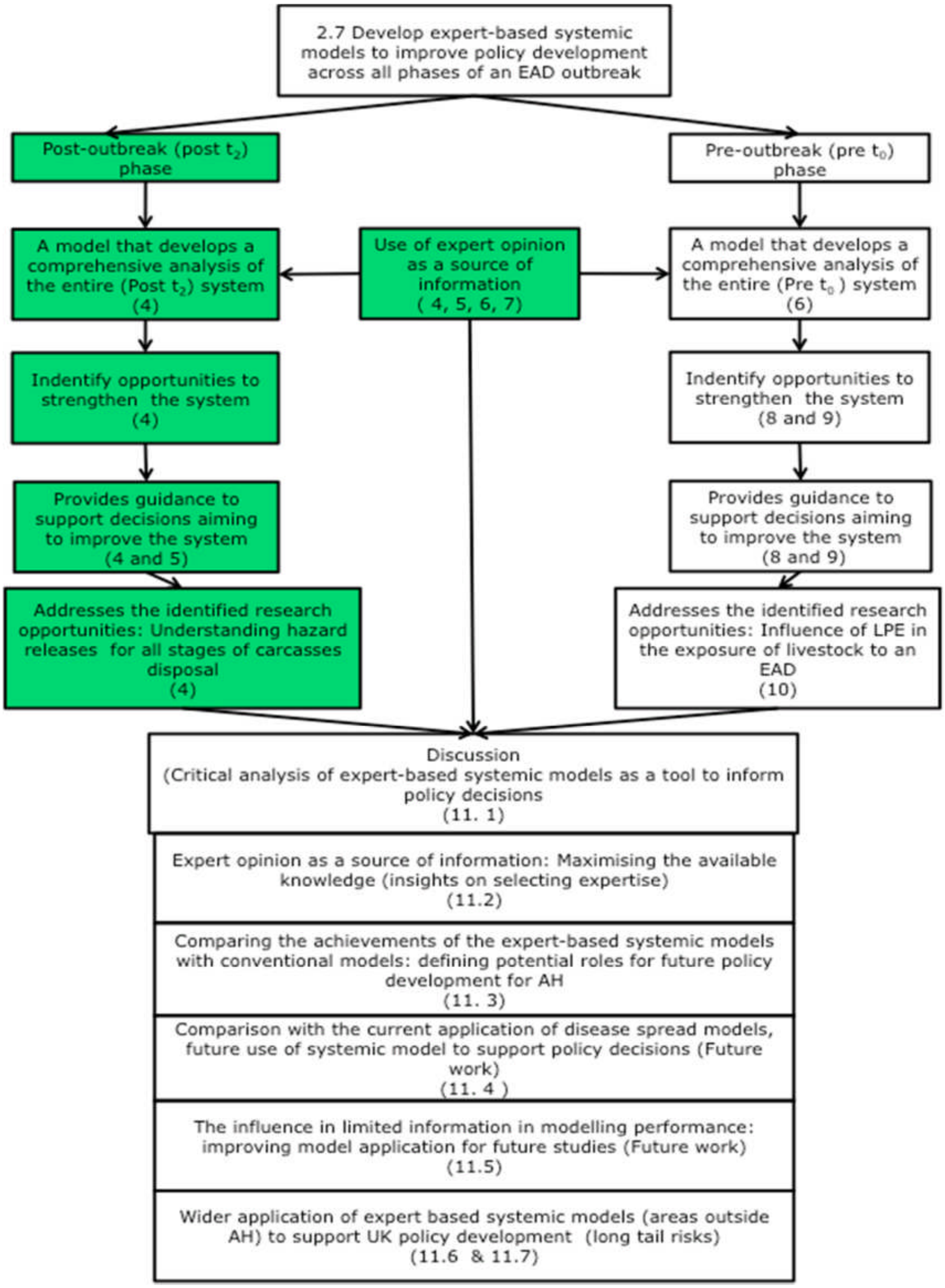

Figure 3.2 Part 1 – Systemic analysis of the post outbreak (post t_2) phase

[Key] The green boxes display research objectives of the experiment. Numbers display the chapters

4 INTERVENTION STRATEGIES FOR CARCASS DISPOSAL – PARETO ANALYSIS OF EXPOSURES FOR EXOTIC DISEASE OUTBREAKS

Published in Environmental Science and Technology Journal:
Delgado, J., Longhurst, P., Hickman, G. A. W., Gauntlett, D. M., Howson, S. F., Irving, P., Hart, A. and Pollard, S. J. T. (2010), "Intervention Strategies for Carcass Disposal: Pareto Analysis of Exposures for Exotic Disease Outbreaks", *Environmental science & technology*, vol. 44, no. 12, pp. 4416-4417 - 4425

4.1 Introduction

Increased prevalence of exotic animal disease (*e.g.*, foot and mouth disease, avian influenza, Newcastle disease, classical swine fever, African swine fever, swine vesicular disease) is a strategic threat to industrialised and developing countries and their economies. Most control strategies are based on a 'stamping out' policy and involve culling of affected livestock and the safe disposal of the carcasses. The extent of carcass disposal operations during outbreaks challenges the waste management infrastructure of the country concerned, posing risks to animal and public health and to the environment (Scudamore et al., 2002; Salminen and Rintala, 2002; Arvanitoyannis and Ladas, 2008). The policy level analysis of these disposal risks (evaluated as potential exposures to human, animal and environmental health) adopts a generalised, qualitative tone, in which hazardous agents inherent to carcass disposal are tracked through a series of unit processes (and associated exposure pathways) to sensitive receptors, be these animal stock, the public or the wider environment (Figure 4.1). Our research (Pollard et al., 2008a) has sought to enhance the utility of generalised policy-level exposure assessments (referred to by Andrews et al. (2005) as ('macro studies') and, by informing contingency planning, improve the pollution control strategies employed during outbreaks, thus reducing the environmental, social and economic burden of these events.

Figure 4.1 Key determinants considered in this generalised exposure assessment for animal carcasses.

[Key] Interventions may prevent release or intercept secondary pathways to receptors. Generalised exposure assessment at the policy level cannot evaluate 'harm' (receptor components) in that exposures are not site-specific, nor contextualised locally in time and space.

We have previously described the policy and international context for our research and published a methodology for generalised exposure assessment, illustrating it for the avian influenza virus (Pollard et al., 2008a). Exotic animal disease outbreaks feature as a key strategic risk within Great Britain (Cabinet Office, 2008), an island nation with a high population density where carcass disposal occurs in close proximity to communities within close public and media view. When outbreaks do occur, large numbers of carcasses require rapid and responsible disposal to avoid the onward transmission of disease to animals and humans, and to prevent environmental harm. Given the challenges of managing this in practice, Great Britain has developed a hierarchy of disposal options that retains some flexibility over the specific choice of waste processing options. This said, without targeted risk management, social and economic costs escalate rapidly. The Anderson, (Anderson, 2002) report, for example, estimates the costs to the UK government alone of the 2001 foot and mouth disease outbreak to be £3bn, employing 1800 vets and 2000 military personnel at its peak.

During disposal, the range of hazardous agents requiring active management extends well beyond the agents of disease to include all hazards associated with a carcass, it's by products, and the infrastructure of disposal (detergents, disinfectants, veterinary medicines, other pathogens, odour and noise). To be cost-effective, risk management must tackle the most potent hazardous agents, be focused upon exposure pathways that exhibit the greatest availability to the significant hazards and address susceptible receptors; being targeted at critical control points (CCPs) where harm reduction can be most effective (Figure 4.1). Used as part of good contingency planning and a preventative risk management approach, such an approach can improve the direction of resources and the quality of management responses on the ground when outbreaks occur.

Here we present an improved exposure methodology, expand its application to a wider range of disease agents, and present a Pareto analysis of the critical exposure pathways for onward control. The revised method addresses some of the practical shortcomings inherent to eliciting expert knowledge in exposure workshops, especially given that for policy analysis, quantitative exposure data is frequently not available (risks are not spatially nor temporally contextualised at this level). Carcass disposal is a multistage process chain, with elements in common with other multistage processes (e.g. food manufacture) where opportunities for intervention must be risk-informed. Clear differences also exist, notably with respect to the open, heterogeneous nature of the natural environment, compared to the closed, batch or continuous manufacturing environment of a food processing plant. Nevertheless, the desire to identify risk-critical exposure pathways is a shared objective so to inform preventative controls.

4.2 <u>Method</u>

4.2.1 Methodological Developments

A general exposure assessment has been described for high pathogenic avian influenza virus. It adopts a heuristic assessment of the relative availability of exposure pathways for each significant hazard using a nominal 1-4 scale. Availability 'scores' are surrogates for the relative likelihood of a significant hazardous agent accessing that specific exposure pathway. So a 'score' of '1' indicates a plausible pathway, but one of negligible to very low availability; '2' represents a plausible pathway of low availability; '3' represents a possible pathway for which there is accepted evidence and medium availability; and '4' represents a probable, direct pathway of high recognised availability (Pollard et al., 2008a). Though admittedly constrained by this nominal classification of relative exposure probabilities, the approach supports decision-makers and presents exposure information in a simple, defensible format, reflecting the complexity of the problem and richness of the supporting elicited evidence. It has been successfully used to direct detailed quantified risk assessments towards particular exposure scenarios on the ground in the heat of an outbreak.

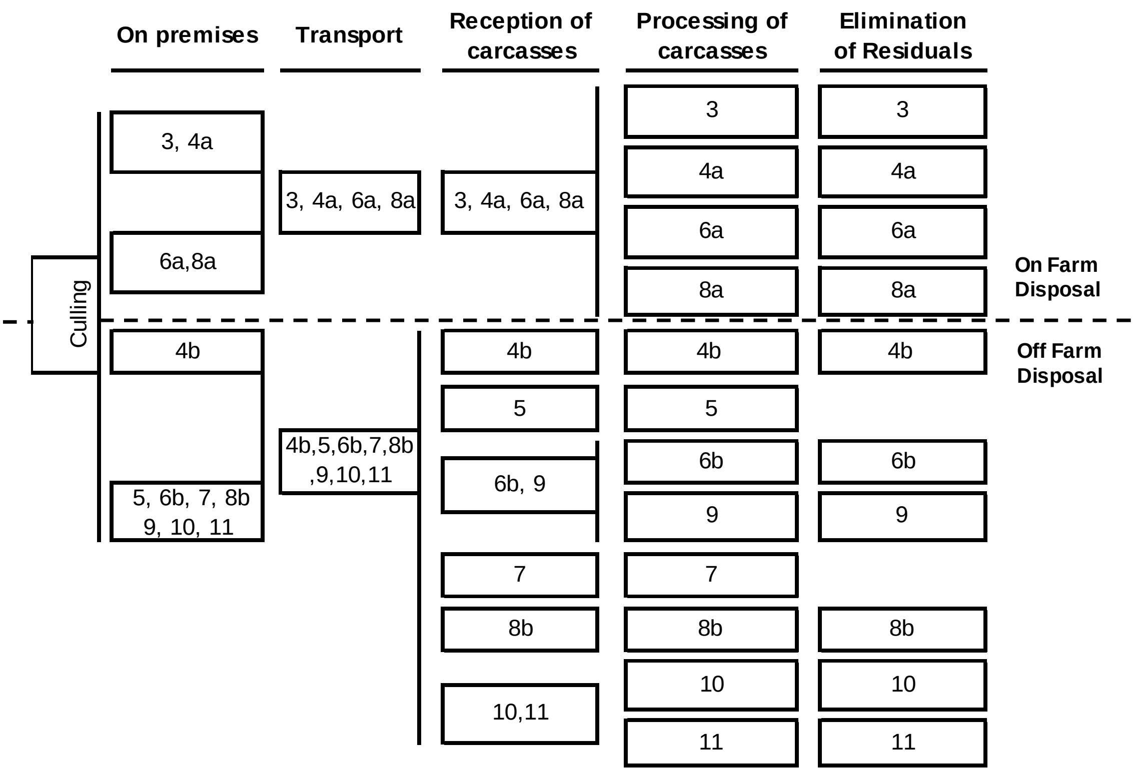

Figure 4.2 Suite of processes considered for carcass disposal.

[Key] Disposal is envisaged as a multistage process from on-premises collection to the elimination of residuals (column headings). Individual disposal options (boxed numbers) adopt individual configurations comprising these stages. Options 1) do nothing, 2a) on-farm storage and 2b) off farm storage were excluded from the figure as they do not adopt the five step disposal. The figure considers the following disposal options chain 3) on-farm burial; 4a) on-farm pyres; 6a) windrow composting on premises; 8a) on–farm in-vessel composting; 4b) off farm mass pyres; 5) mass burial/inert controlled landfill; 6b) windrow composting off-premises; 9) air-curtain/mobile incinerators; 7) non-hazardous/hazardous controlled landfill; 8b) off-farm, biogas/anaerobic digestor/in-vessel composting; 10) pressurised or atmospheric rendering or alkaline hydrolysis; 11) gasification and pyrolysis, licensed controlled incinerators

The revised methodology was developed using an expert workshop held at Cranfield University, in January, 2008. The workshop considered a fuller range of notifiable exotic animal diseases (the original approach was limited to avian influenza), including foot and mouth disease (FMD), classical swine fever (CSF) and Newcastle disease, and incorporated some methodological improvements. Technical domain specialists (e.g. veterinary specialists, public health experts, environmental exposure assessors, waste technologists, hydrogeologist, air quality experts) were assembled from Defra, the

Animal Health Agency, the Environment Agency, the Scottish Environment Protection Agency and the Health Protection Agency, alongside the research team. The research agenda within the workshop was concerned with: (i) improving the record of decision on the hazard screening exercise for various diseases; (ii) distinguishing between impacts for animal health, public health and the environment; (iii) collating waste technologies into categories that allowed greater consistency of treatment in the exposure assessment (Figure 4.2), which is an extensive combinatorial exercise; and (iv) reviewing the metrics of the exposure assessment with a view to improving the utility of the data for contingency planning.

The workshop structure uses a sequence of expert elicitations. Expert knowledge on the likelihood of exposure for the significant agents along individual process chains was secured and presented within the workshop for a critical comparison of each process chain (Figure 4.2). Quality checking of all pathway scores was undertaken for the common stages of each pathway (Figure 4.2), and then for the total pathway score; first by the experts within the workshop and then independently off line in order to check consistency within and between process chains. Using this approach, experts contribute individual domain expertise and also to a collective view for each disposal pathway, with an independent 'arm's length' quality audit being completed shortly after the workshop. A full hazard screen for significant hazards (Table 4.1) and initial exposure assessment was completed on 14th-15th January 2008. Subsequently, a sub-group met to finalise the exposure assessment and recommend improvements to the presentation of the exposure metrics which were held in an Excel™ spreadsheet. The quality audit was undertaken on the metrics (February 2008) by members independent to the research team. Recommendations from this audit were implemented and a final exposure assessment prepared that:

- modified the hazardous agents list in order to comprise a wider set of etiological agents, including avian influenza (control against initial methodology), Newcastle disease (poultry), (foot and mouth disease (cattle, pigs, sheep), bovine spongiform encephalopathy (cattle), scrapie (sheep), swine vesicular disease and African and classical swine fever (pigs);
- specified which receptor (animal health, public health, the environment) the hazard was likely to present significant concern to, redefining animal health impacts as solely for domestic and livestock animals (Table 4.1);
- specified for which receptor exposure was most likely to be of concern; and
- formally captured qualifying comments from the expert group (Table 4.1).

Having identified the significant hazards of carcass disposal, the methodology does not attempt to distinguish further between the toxicological/pathogenic potencies of those hazards deemed by experts to be significant (Table 4.1), though the relevance of the potential harm posed to animal health, public health or the environment was considered by reference to the availability of the pathway to these receptors.

Hazardous agent Filter:	1- Significant effects?	2-Evade destruction?	3-Significant quantities?	Commentary
Biological agents				
Foot and mouth disease	Y A)	Y	Y	
Classical swine fever	Y A)	Y	Y	
Newcastle disease virus	Y A)	Y	Y	
Salmonella spp.	Y A/H)	Y	Y A/H)	Present in UK pigs, cattle and sheep. Prevalence falling in recent years but still an important pathogen. Control of salmonella strains in poultry very good)
Bioaerosols actinomycetes, aspergillus *spp.*)	Y	Y	Y	
Influenza H5, H7)	Y A/H)	Y	Y	High mortality zoonoses with poor penetration
Influenza other A strains)	Y A/H)	Y	Y	Generally low mortality / morbidity in humans
Campylobacter spp	Y A/H)	Y	Y	Prevalent pathogen; several pathways, low dose exposure causes disease in animals and humans
Coxiella burnetii Q-fever)	Y A/H)	Y	Y H)	Recently recognised zoonotic potential. Association with slaughter and disposal.
African swine fever	Y A)	Y	Y	
Bovine spongiform encephalopathy prion	Y A/H)	Y	Y E)	Assume controls are in place; treated as a chemical during BSE 1996-2001, hence environmental relevance
Cryptosporidium spp.	Y A/H)	Y	Y	Often of limited morbidity
Scrapie	Y A)	Y A)	Y E)	Assume current controls are in place
Swine vesicular disease	Y A)	Y	Y	
Chemical agents				
Ammonia, ammoniacal nitrogen and nitrates	Y	Y	Y	Present naturally and in high strength leachate from decaying carcasses. Significant potential impact on water bodies, especially ground waters.
Detergents phosphates, LAS)	Y	Y	Y	From cleansing and disinfection - potential impact on aquatic environment through percolation/runoff.
Disinfectants formaldehyde, phenols, hypochlorite, peroxide, QAS-salts, FAM30, Virkon S)	Y	Y	Y	Used routinely on poultry units for biosecurity, but in the event of an outbreak of avian influenza usage will increase. Carcasses will be sprayed with disinfectant prior to disposal. Most disinfectants contain listed priority substances and should not be discharged to controlled waters.
Biochemical oxygen demand BOD)	Y	Y	Y	
Veterinary medicines in carcase; e.g. pesticides, antibacterials, coccidiostats, barbiturates)	Y	Y	Y	If poultry are killed before they would normally have been, there is a possibility that veterinary products may be present in the body at elevated levels within the normal withdrawal period). If killing is by lethal injection there may be barbiturates present – potential impact on the environment
Methane	Y	Y	Y	
NOx	Y E)	Y	Y	Derogation of local air quality
Particulates	Y	Y	Y	Amenity and public health impact on local communities
Polycyclic aromatic hydrocarbons	Y E)	Y	Y	
SOx	Y E)	Y	Y	Derogation of local air quality
Kerosene and other accelerants e.g. Feedol)	Y E)	Y	Y	
Breakdown products e.g. pesticide residues, metabolites)	Y A/H/E)	Y	Y	
Heavy metals Pb, As)	Y	Y	Y	
Dissolved organic carbon, total organic carbon	Y	Y	Y	
Extreme of pH	Y	Y	Y	Mostly from use of disinfectants

Benzene, toluene, ethylbenzenes, xylenes	Y	Y	Y	Combustion by-products – potential impact on air quality.
Wood resins and chemicals in wood preservatives e.g. PCP, CCA)	Y	Y	Y	Poor combustion could release hazards – impact on air quality and ash quality.
Dioxins, furans, PCBs	Y	Y	Y	
Insecticides permethrins, organophosphates)	Y	Y	Y	
Amenity, nuisance impacts				
Odour	Y	Y	Y	Amenity and public health impact on local communities
Noise	Y	Y	Y	Amenity and public health impact on local communities
Derived products litters, slurry, manures)	Y	Y	Y	High BOD
Milk / treated milk	Y	Y	Y	High BOD
Smoke	Y	Y	Y	Amenity and public health impact on local communities
Ash	Y	Y	Y	Public nuisance effects and TSEs if low temperature
Waste treatment / wastewater treatment residues e.g. alkaline hydrolysis residues; sludges; residual farm shop wastes)	Y E)	Y	Y	Even with controls in place concerns regarding waste residues
Organic fertiliser and soil improvers	Y E)	Y	Y	

Table 4.1 Table of hazards and process of hazard screening used by experts to selection

4.2.2 Exposure Assessment and Pareto Analysis

The processing of large numbers of elicited pathway availabilities for multiple agents and associated hazards may introduce inconsistencies in expert views as they apply their domain knowledge between similar unit processes for each disease. In short, the task of processing multiple combinations of hazardous agents and exposure pathways for human, animal and environmental receptors becomes highly complex for participants because of the large number of combinations involved. Improvements were made to the exposure assessment methodology for ease of data processing and visual of the key drivers of exposure within the spreadsheet: (i) the introduction of a benchmarked 'base case' for each process chain against which each process could be evaluated; (ii) restructuring the model to collate each of the disposal options and present them as a single worksheet, allowing pathways (Table 4.2) to be directly compared, securing a greater level of consistency; (iii) presentation of individual pathway scores within the model to allow a direct comparison of the exposure metrics for each disposal route.

Medium	Pathways	Abbreviation
ABOVEGROUND	Deposition onto crops & consumption	AG dep crop cons
	Direct contact	AG dirc cont
	Ingestion	AG ing
	Inhalation	AG inh
	Noise (nuisance)	Noise
	Odour (nuisance)	Odor
	Smoke (nuisance)	Smoke
	Wild animal consumption	AG wild cons
	Wild animals (spread)	AG wild sprd
SURFACE-WATER	Consumption of animals	SW anim cons
	Crop irrigation & consumption	SW crop irr
	Direct contact	SW dirc cont
	Fish or shellfish consumption	SW Shellfish
	Ingestion of water	SW ing
	Inhalation	SW inh
	Inhalation of irrigation water	SW inh wtr
	Leaching from SW to GW	SW to GW
GROUNDWATER	Consumption of animals (Private)	GW anim cons (p)
	Crop irrigation & consumption (Private)	GW crop irr (p)
	Direct contact (Private)	GW dirc cont (p)
	Fish or shellfish consumption (Private)	GW shellfish (p)
	Ingestion of water (Private)	GW ing (p)
	Inhalation (Private)	GW inh (p)
	Inhalation of irrigation water (Private)	GW inh wtr (p)
	Consumption of animals	GW anim cons
	Crop irrigation & consumption	GW crop irr
	Direct contact	GW dirc cont
	Fish or shellfish consumption	GW shellfish
	Ingestion of water	GW ing
	Inhalation	GW inh
	Inhalation of irrigation water	GW inh wtr
GROUND TO SURFACE-WATER	Consumption of animals	GS anim cons
	Crop irrigation & consumption	GS crop irr
	Direct contact	GS dirc cont
	Fish or shellfish consumption	GS Shellfish
	Ingestion of water	GS ing
	Inhalation	GS inh
	Inhalation of irrigation water	GS inh wtr

Table 4.2 Full suite of exposure pathways considered

Effective risk management infers the capacity to intervene at critical control points, thus using resources wisely for targeted optimal risk reduction. Here we evaluated pathways contributing most to the overall exposure using a Pareto analysis (Craft and Leake, 2002). The approach has been described in the management literature by Frakes and Fox (1996), Fox et al. (2010) and Omachonu and Ross (2004), and exemplified for multi-barrier systems comprising multiple unit processes within the food industry by Arvanitoyannis and Savelides, (2007). By convention Pareto charts consist of histograms, the lengths of which are proportional to the arithmetic mean exposure (y axis), organised from left to right from highest to smallest contribution (x-axis). The right hand y axis represents the cumulative contribution to overall exposure. Consistent with the Pareto principle, a nominal threshold value was set at 80% (black vertical line), where the group of pathways to the left of the line is responsible, in aggregate, for 80% of the exposure pathway availability, as ranked by workshop experts.

4.3 Results and discussion

4.3.1 Analysis

Table 4.1 presents the list of significant hazards identified by the expert workshop. Figure 4.2 provides a map of the unit processes, many of which are common for the range of disposal options considered. Table 4.2 presents the full set of exposure pathways considered in this analysis across all disposal options and unit processes. Using exposure pathway 'availabilities' elicited in the expert workshop, a set of a Pareto charts were constructed for each of the processes represented in Figure 4.2 (numbered) by reference to the distribution of exposures at each of the 5 stages (Figure 4.3), and then by the individual exposure pathways associated with each of the 5 stages of carcass disposal (Figure 4.4). This allows screening and prioritise to be applied at two different levels: (i) at the process chain level, prioritising process chains according to the potential risk of exposure, and identifying critical control points for managing exposures along the process chain; and (ii) of key exposure routes within each process step, allowing pathways to be considered irrespective of disposal route.

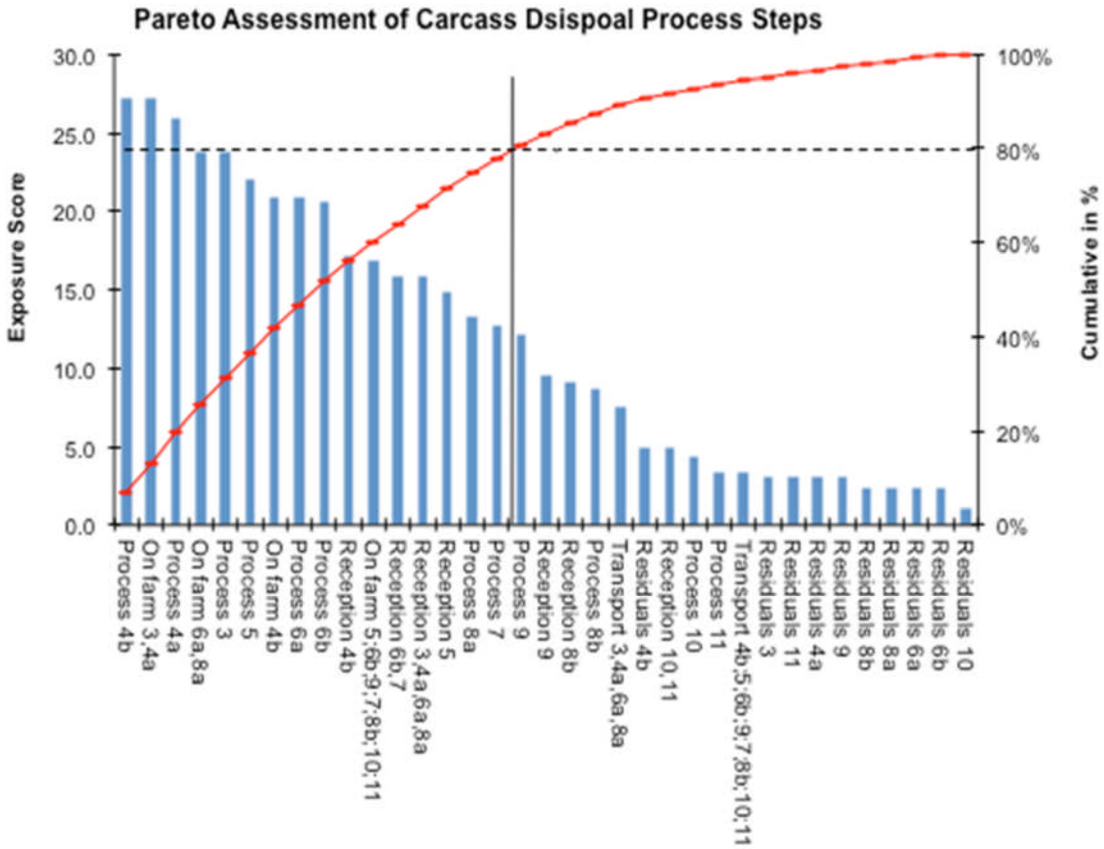

Figure 4.3 Screening and prioritising carcass disposal steps, independently of process category

[Key] Process categories are 3) on-farm burial; 4a) on-farm pyres; 6a) windrow composting on premises; 8a) on–farm in-vessel composting; 4b) off farm mass pyres; 5) mass burial/inert controlled landfill; 6b) windrow composting off-premises; 9) air-curtain/mobile incinerators; 7) non-hazardous/hazardous controlled landfill; 8b) off-farm, biogas/anaerobic digestor/in-vessel composting; 10) pressurised or atmospheric rendering or alkaline hydrolysis; 11) gasification and pyrolysis, licensed controlled incinerators

Consider Figure 4.3 summarising those processing stages contributing most to exposure across the full set of carcass disposal options. The waste processing of carcasses using on-farm pyres option 4b) presents the greatest potential for exposure, followed by the collection of carcasses on farm for onward burial or pyre disposal. This approach represents a conceptual move towards a modular, ‘object-oriented’ approach to the exposure assessment. Here, 80% of the total availability of onward exposures to human, animal or environmental receptors is represented by the 16 processes including and above Process 7 in Figure 4.3; being dominated by on-farm collection and carcass processing, demonstrating the necessity of effective controls during the early stages of culling and waste processing.

Next consider Figure 4(a) to (e) which, in concert, allows a visual comparison of the importance of all those exposures represented in Table 2 across each stage of disposal in turn (Figure 2) for the disposal option of mass pyres (option 4b). Ground- and surface water exposure pathways dominate on premises, with noise and odour nuisance prevalent for mass pyres, consistent with the experience that contamination can have origins in multiple sources in the early stages of disposal (Ritter, 1995; Environment Agency, 2001; Cumby et al. 2004). These pathways are candidates for control and map across to experiences during outbreak management. By illustration, among the specific environmental impacts reported part-way through the 2001 foot and mouth disease outbreak requiring effective management (Environment Agency, 2001a, b), were (i) a large number (ca. 200) of reported water pollution incidents from the surface run-off of blood and carcass fluids early on in the crisis, when culling rates outstripped disposal capacity; though few of these resulted in significant water pollution (ca. only 3 high category pollution incidents from slurry spill and disinfectant run-off); (ii) the generation of large quantities of ash from constructed animal pyres (typically 15 tonne ash per 300 t pyre) required onward containment and disposal; (iii) localised, short-term decreases in local air quality during pyre burning (Lowles et al., 2002; Department of Health, 2001).

Contrast this analysis with the Pareto charts prepared for fixed plant thermal treatment options evaluated in concert as gasification, pyrolysis and licensed controlled incinerators (Figure 4.5a) to e)). The exposures generated whilst carcasses are gathered on premises remain with a reduction in exposure in the later stages of disposal compared to the mass pyre option, e.g. reception and processing of carcasses and elimination of residuals, can be observed. In the UK, waste incineration installations must operate within standards required by the waste incinerator directive (Defra, 2009c). The WID sets benchmark criteria for reception and processing of waste and through the landfill directive the elimination of residuals. The tougher controls imply that “incineration plants” present a higher level of technical sophistication and protection (Defra, 2009b). Despite this, aboveground exposure pathways, smoke and noise are worthy of consideration.

4.3.1 Communicating Risk and Designing Interventions with Policy Experts.

This work represents the next stage in the chronological development of methods used to communicate the extent and significance of exposures during carcass disposal. The visual of conceptual models of exposure and of summary data for policy level decisions are critical if compelling arguments for policy improvements are to be justified. Early communications (2001) adopted qualitative reasoning and summary schematics to compare the waste technologies used for carcass disposal. Rapid qualitative risk assessment, backed up by selective quantitative background studies on air pollution, for example, was used to compare the number of exposure pathways associated with specific disposal options (DH, 2001); Figure 4.6; the number of pathways acting as a surrogate for the extent of public and environmental risks. Since (Pollard et al., 2008a), we have move beyond a discussion of waste technology in isolation and have considered the full process chain of disposal, ranking the relative availability of exposure pathways, and allowing a qualitative comparison of the distribution of exposure for hazards associated with avian influenza from farm through to the disposal of residuals (Pollard et al., 2008a). Here, we now offer an object-oriented approach that seeks to present, semi-quantitatively, the distribution and contribution of exposures both across the process chain and by environmental pathway irrespective of the unit process, so allowing environmental regulators to focus on specific environmental receptors during an outbreak. We also extend the analysis to a broader suite of exotic diseases.

The Pareto charts demonstrate the level of exposure associated with each stage of disposal (Figure 4.3) and with specific pathways considered for each stage (Figure 4.4 and 4.5). Thus the charts assist in the synthesis of these generalised, policy-level exposure assessments and acts as an important communication tool for policy makers, allowing for the comparison between the level of exposure expected between discrete waste processing options, but importantly, also along the length of disposal chains (Figure 4.2). Qualitative comparisons can, for example, be observed between exposures associated with collection on premises / transport and active carcass processing / residuals management (Figure 4.4 and 4.5). By making the distribution of exposure availabilities visible, we bring an improved level of understanding on exposure across the process chain to the debate, allowing policy officials to direct risk management efforts accordingly and communicate a rationale for intervention priorities. Of course, decision-makers must integrate the analytical insights that exercises such as this generate within the context of UK, European Union and International standards and norms. The relationship between analysts and decision-makers and the associated challenges of risk-informed policy design and delivery are well characterised (Sawicki and Craig, 1996; Andrews, 2002). This said, these analysis offers a firm, evidence based assessment of the disposal options required in a modern policy and regulatory environment. The principal policy benefit from this work has been in operationalizing Defra's contingency plans during outbreaks. Whilst these are published and regularly reviewed, the majority of stakeholders and interested parties read them only in the event of an outbreak when it impacts on their own operational activities. Defra has used this research to support its stated position that the risks to human health, animal health and the environment from our chosen disposal routes are minimal. This research has provided an evidence base to support a single disposal hierarchy in Defra's published plans. Without this, it would have been difficult to state, with any authority, whether existing controls were adequate. Defra is now considering extending the principles and practice communicated in this work to the development of a framework for assessing the risks of carcass disposal for new and emerging diseases. Defra believes the research also has relevance to the evaluation of other putrescible wastes that may need to be disposed; such as, for instance, during a terrorist attack or accidental discharge in a chemical, biological, radiological or nuclear (CBRN) incident. The research clearly highlights the large number of high risk pathways during the initial phases of carcass disposal and during the collection and loading of carcasses on farm. This has resulted in a review of operational guidance and modifications to the guidance on selection of culling sites, rapid removal of carcasses, containment of wash water and the loading of carcasses into leak-tested trucks. Defra has also used this research to develop a 'landfill protocol' for the disposal of carcasses in permitted landfill sites.

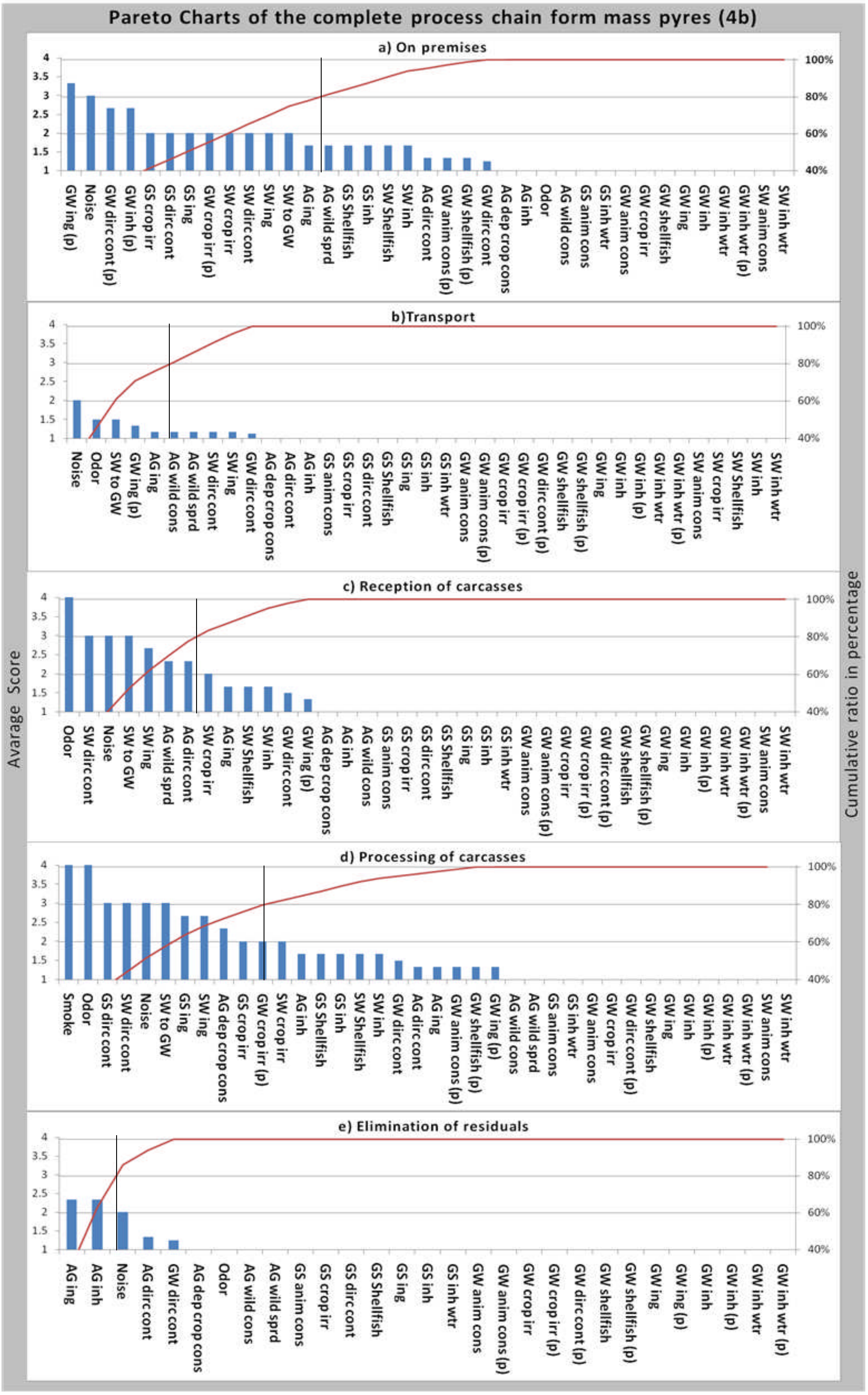

Figure 4.4 Pareto charts (for illustration) of the mass pyre disposal chain.

[Key] Five charts are displayed, one for each step, presented top-down: a) on premises; b) transport; c) reception of carcasses; d) processing of carcasses; and e) elimination of residuals. The horizontal axis presents the abbreviated reference for each of the pathways (see Table 4.2).

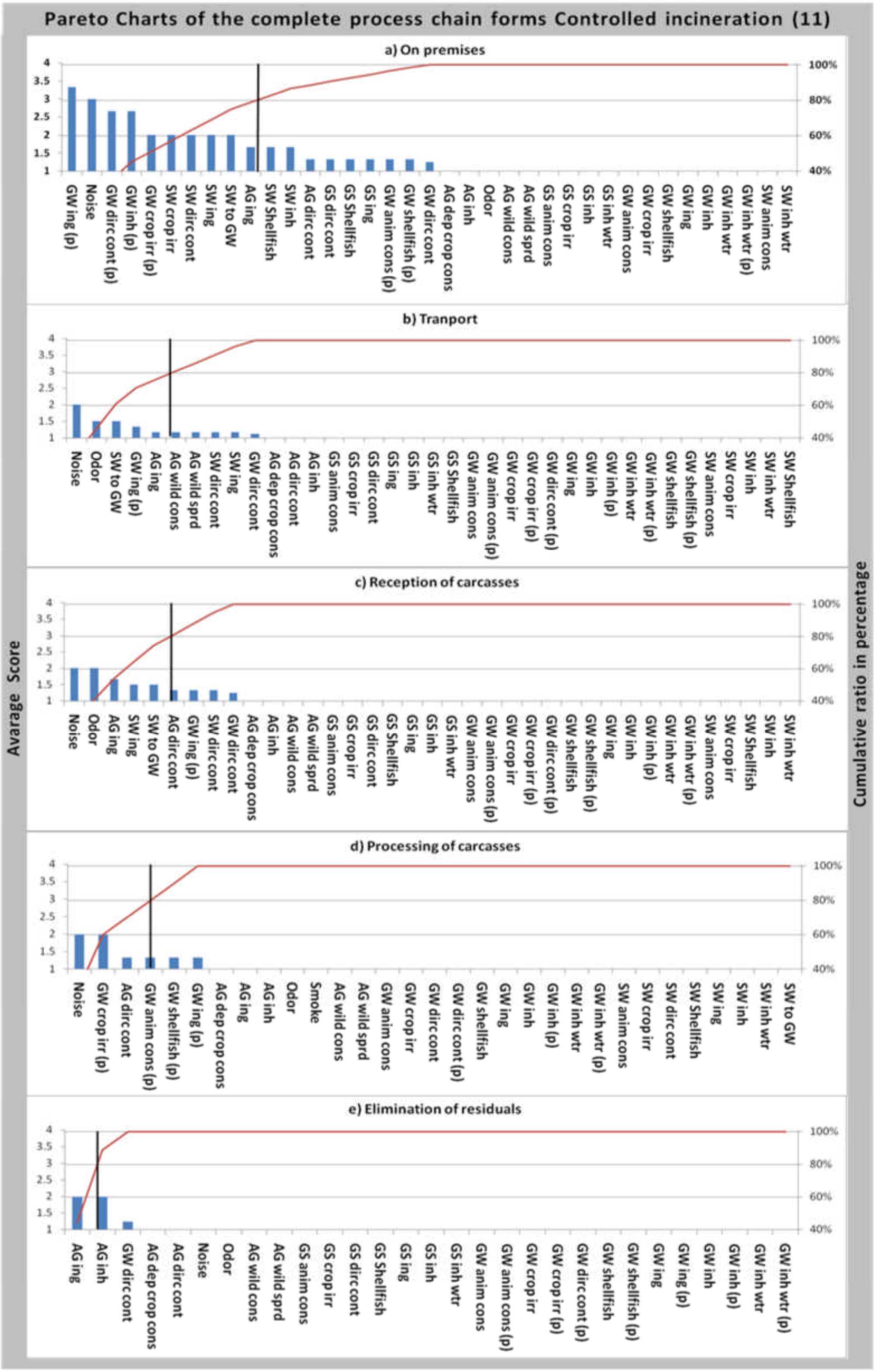

Figure 4.5 Pareto charts for illustration) of the controlled incineration disposal chain

[Key] Five charts are displayed, one for each step, presented top-down: a) on premises; b) transport; c) reception of carcasses; d) processing of carcasses; and e) elimination of residuals. The horizontal axis presents the abbreviated reference for each of the pathways (see Table 4.2).

These implementation benefits are encouraging. The tools developed in this research embody well recognised limitations and are but one way of communicating multiple contributions to exposure in a complex decision environment. Our selection has been made by reference to various alternative tools, some of which have been discarded on the basis that either they were not appropriate for the study context and/or because the data produced during the elicitation workshop was not of the relevant format for correct application of the tool. These, other options, for reference, include the consideration of so-called Ishikawa (fishbone) diagrams, which emerged from the discipline of production management, adopted as quality control tools within the manufacturing sector (Francisco, 1991; Richard, 2007). However, they are perhaps best suited to closed engineered systems where defined product lines, process flow sheets and pathways are characterised by materials flow in formalised product lines or via contained (e.g. piped) infrastructure. Here, rather, we were concerned with the release of hazardous chemical and biological agents at process points within an open heterogeneous system (the environment) and in assessing multiple exposures to a range of receptors along a process chain interacting with the wider environment. In this study, the distribution of opportunities for exposures of differing probability (Figure 4.6) is critical hence the selection of the Pareto chart. In closed systems by contrast, as (Arvanitoyannis and Savelides, 2007) displays for food manufacture and the contamination events that might spoil food products, there is the potential to adopt both tools in a single study. With concerns about the methodological biases inherent to the use of risk tools designed for closed systems being applied to open environmental systems, we discarded application of fault and event tress in this particular case, although others have adopted these, say for BSE prion exposures via environmental pathways (Comer et al., 1998).

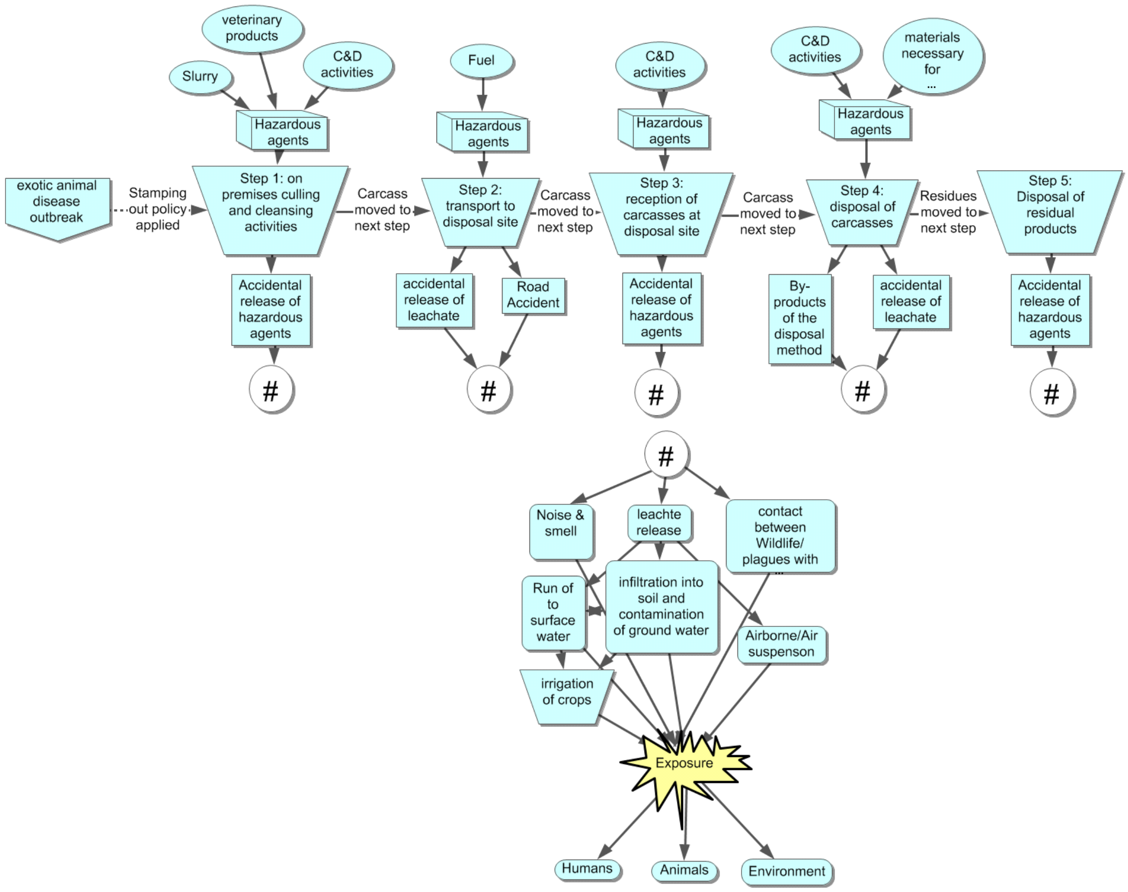

Figure 4.6 Contribution of multiple sources of hazards, pathways and receptors to an exposure pool for onward Pareto analysis

[Key] The picture describes the generic carcass disposal chain, where the ♯ symbol describes the same suit of pathways for all stages of disposal (Table 4.2).

In our study, 38 exposure pathways (Table 4.2) had to be assessed for each of 35 disposal steps defined (Figure 4.2); this requiring the assessment of more than 1300 pathways of exposure. Even with a nominal ranking approach, workshop facilitators needed to work to ensure that expert fatigue from processing the sheer number of combinations did not influence negatively the quality of the results. With these choices made and as configured, the format of the output does not yet allow analysts to: i) infer the importance of one individual hazardous agent above another; ii) identify the source of the hazardous agent; iii) evaluate the harm to human receptors, animals or the surrounding environment. These are requirements of site-specific risk analysis in the operational setting that can be informed by high level analysis but not determined at this macro-level.

Notwithstanding this critique, the limitations and the availability of other tools that might also be applied to communicate these messages, we believe this to be the first application of Pareto analysis to generalised policy-level exposure assessments. We reassert the view that risks to receptors during carcass disposal activities are not confined to the waste processing of animal carcasses in isolation, but rather present from farm until ultimate disposal of residuals. Pareto analyses can be used to prioritise exposure pathways according to their contribution to the overall exposure potential across the disposal chain (Figure 4.6) and can assist in communicating the complexity of a multi-attribute problem to decision-makers. Adopting an object-oriented approach allows efficiencies to be secured in both the analysis itself and in the design of risk management measures that have common features irrespective of the waste processing option. Measures that address priority pathways during disposal are likely to be most effective when a range of disposal strategies is applied from a hierarchy of options which is a necessity in Great Britain given the structure of the waste management sector, the legislative constraints on certain options and the intense and close public and media scrutiny that accompanies disease outbreaks. These are important considerations for national policy makers and international organs seeking to develop guidance on the processing of animal carcasses (International Organization for Standards, 2010).

4.4 Acknowledgements

We thank Defra and the Animal Health Agency for funding this work and the expert participants from the Health Protection Agency, Environment Agency, Scottish Environment Protection Agency, Welsh Assembly, Scottish Executive and the Department of Health. Peter Tangney and Jens Evans Environment Agency) conducted an independent audit of the exposure assessment and Sophie Trombini MSc, Cranfield University 2007/8) assisted with formatting the Pareto analysis. JD is funded by Cranfield University. The Risk Centre is funded by Defra, EPSRC, NERC and ESRC under grant EP/G022682/1.

5 MODELLING THE ENVIRONMENTAL RELEASE AND EXPOSURE OF HAZARDOUS AGENTS RESULTING FROM CARCASS DISPOSAL ACTIVITIES

5.1 Introduction

Globalisation and the intensification of trade have heightened the vulnerability of developed countries to exotic animal diseases (Otte et al., 2004). As a result, it is estimated that developed countries are no more protected today than they were two decades ago from the threat of an exotic animal disease outbreak (EFSA, 2006). The damaging social and economic impacts of these outbreaks are the reason to ensure preparedness against such events (Anderson, 2002; Scudamore et al., 2002; Morgan and Prakash, 2006). The UK could adopt a stamping out policy to accelerate the process of disease eradication, thus minimising the duration of trade restrictions (Otte et al., 2004; Scoones and Wolmer, 2006). Stamping out policies involve culling all infected animals as well as dangerous contacts alongside the disposal of animal carcasses (Scudamore et al., 2002; Defra, 2009b; Defra, 2007b). This can lead to the destruction of millions of carcasses and release of harmful products to the environment (Defra, 2011b; EA, 2001; Marsland et al., 2003; Lowles et al., 2002). In practice governments accept responsibility for coordinating the disposal activities to minimise environmental and health impacts (Otte et al., 2004; WHO/FAO/OIE, 2004).

Delgado et al. (2010) developed a model to study a wide range of carcass disposal options and identify the release and exposure pathways of greatest concern for each, thus informing policy development and consideration of mitigation measures. As with all elicitation models, there was a trade-off between the resources available for elicitation and modelling detail that could be achieved. The model used a semi-quantitative template to enable a quick elicitation process. However, at the expense of a detailed output, resulting in that the model does not specify the hazards released and those exposed by each pathway. This chapter presents a model that compliments this output by specifying the hazards exposed for each individual pathway. This represents an exploratory exercise to identify the hazardous agents that pose a risk of environmental contamination and disease transmission. The model aims to overcome information gaps left by the previous assessment which challenge the interpretation of the results (Chapter 4) (Delgado et al., 2010). A failure to capture the expert rationale and assumptions used to assess exposure generated these gaps. These omissions include failures to specify the activities considered for each stage of disposal, the hazardous agents released by those activities and the hazards considered for the evaluation of each individual pathway. The additional information produced by this model adds context to the semi-quantitative score previously produced. Risk contextualisation enables the development of hazard specific risk management solution as opposed to generic ones addressing any one hazard included in the hazard list.

5.2 Method

The process of development was designed to ensure synergy between the outputs produced from this model and the work performed in Chapter 4 (Delgado et al., 2010). Thus ensuring accessible and complete information is presented to a decision making body. The model presented here adopts the same object oriented framework, however using a different modelling approach to study the fate of the individual hazards. Here the approach diverges from the conventional methods of developing expert based qualitative models (OIE, 2011c; Pollard et al., 2008a; DH, 2001) and instead applies a hybrid model, using expert judgement and computer based modelling. Conventional qualitative approaches require an extensive amount of input data. This increases the costs and time necessary to complete the elicitation exercises and can overburden experts thus compromising the quality of the data due to tiredness (O'Hagan, 1998; Liou, 1992). Instead, this model reduces expert involvement to a minimum, whilst respecting the objectives and framework of the original assessment. This was achieved through the association of expert knowledge with object oriented computer programming, where experts were used to verify the hazards profiles, instead of assessing each individual pathway.

5.2.1 Summary review of Delgado's model

This section presents a summary of the framework presented in Chapter 4 (Delgado et al., 2010), to explain the selection of the model and the output format adopted here. The framework applied uses basic building blocks, as follows:

- The assessment studied 27 disposal options, with each option containing 5 disposal stages (Figure 4.6). Similar stages were aggregated to reduce the number assessed from over 100 to 35 (Figure 4.2).
- The same 28 release and exposure pathways were assessed for each disposal stage (Table 4.2).
- A list of hazardous agents was considered when assessing the each pathway for potential release and exposure to receptors (Table 4.1).

Results were presented at two levels:

- First level output - ranks the disposal stages considered for each option (Figure 4.3).

- Second level output – ranks the pathways for each disposal stage (Figure 4.4 and Figure 4.5).

5.2.2 The model and previous work

The main challenge for modelling the environmental fate of hazardous agents arises from the diversity of agents considered. Chemical, biochemical and biological agents, behave differently when released into the environment or in contact with receptors, Table 5.1. To accommodate these differences in hazardous agent behaviour, the model adopts a qualitative template that is associated to the computer model. All models including those that are computer based are simplifications of complex realities. This is defined as *abstraction*, which delivers control to the assessor to tailor programmes according to the output needs and/or available data (Frantz, 1995). The computer model replaced complex expert judgments characterising the fate of multiple agents. Consequentially, it facilitated moving away from a demanding and generic elicitation process to one that focuses on a small number of specific hazard variables. By focussing solely on a qualitative character of the hazardous agents and environmental releases, instead of assessing each pathway individually, it simplified and reduced the quantity of input data necessary.

Smart application of information allows for quicker and less costly assessments. Similarly, managing the model's output was an important step to control input data. Since this model compliments existing results, it focuses solely on the identification, e.g. presence/absence, of hazards at the end of each pathway. This approach allows us to exclude more comprehensive models that require further detailed data, such as multimedia or mechanistic models (Vose, 2008; Mackay et al., 2001).

5.2.3 Computer Modelling

Developing a computer model requires a clear and unambiguous description of the problem. The OIE guidelines were followed when describing the system (OIE, 2011c; Stirling and Scoones, 2009). The framework is described under the following terms: *i).* The *Environment* refers to the state of the environment from the location of hazard release to the area where harm may be expected. The environment is represented by pathways of exposure (Table 4.2). *ii).* The *hazards* represent harmful substance released into the environment. *iii).* The *environmental releases* describe the activity that triggers the interaction between the agents, environment and the receptors (Figure 4.6). The methodological boundaries of the model ensure that the output remains useful and accurate within the needs of the decision makers. The model was developed with consideration of the assessments objective and the terms described above.

A pathway represents one scenario of release and exposure of the hazardous agent to receptors; these are separated in to four groups according to the exposing medium; above-ground, groundwater, surface-water and ground to surface water pathways, where the intervention from several factors, such as carrier and vectors are accounted for. Each media is considered for multiple pathways. These are represented by a series of filters through which hazards can either overcome or be captured, depending on their physical/chemical properties. Each pathway is therefore defined by a unique combination of filters which influence successful exposure to receptors.

The hazards represent the harmful substances released onto the environment. The data collection focuses on characterising the hazards chemical and/or biological properties, in relation to the barriers defining the environment. Table 5.1 displays the input data entered into an Excel ^{TM} spreadsheet and contains the information: *Column* one displays the hazards list, where each *row* represents single hazards or a cluster of hazards. The table contains a profile of each hazard, according to its physical/chemical properties. The first nine *columns* represent the properties associated with each individual or agglomerate of hazards. From the left to the right the first four columns describe the capacity to migrate through media, (soil, water, air and resurfacing for an aquifer groundwater to surface water). The following two columns describe animal transmission modes: vector or bioaccumulation. The seventh, eighth and ninth columns represent the exposure to receptors: direct contact, ingestion and inhalation.

The environmental releases resulting from the activities performed within each stage of disposal are represented by the remaining columns (Table 5.1). Columns from the 10th to the 14th characterise environmental releases in the disposal chain, considering all five disposal stages. It was assumed that the same activities are performed in all considered on-farm stages. Therefore, these share a single profile (tenth column). A similar assumption was made for the transport and reception stages. Columns twelve and thirty display the profiles for all considered transport and reception stages respectively. In contrast, the processing and residual stages present an array of activities associated the disposal option selected, therefore these are characterised by specific profiles, displaying different environmental releases. In the input-sheet, these were captured in the remaining columns.

Data were recorded using a binary system, where (1) represents hazard progression against the respective barrier (failure to contain) and (0) represents containment of that hazard containment). The hazards profiles where generated based on the information gathered for governmental databases regarding chemical and disease agents (OIE, 2011b; ATSDR, 2010; NPI, 2010). Due to the significant influence of qualitative input and assumption when developing the disease profiles, experts were used to complete and verify the input data. Furthermore, uncertainties over success/failure to overcome a particular barrier were recorded though the introduction of a third class, where (2) represents an uncertain parameter. This class assumes a worst-case scenario, thus in doubt the hazard overcomes the barrier. Uncertainty was identified in the output by a monochromatic (scale grey) in the output frame, Table 5.2 and Table 5.3.

List of hazardous agents	Hazardous Agent Profile									Agent release per disposal stages				
	Soil	Water	Air	GwSw	Vector	Bioaccumulation	Direct cont.	ingestion	Inhalation	farm	transport	reception	process *	residuals *
Ammonia, ammonium	1	1	1	2	0	0	1	1	1	1	1	1	1	1
Quaternary ammonia	1	0	1	2	0	0	1	1	1	1	0	1	1	1
Iodine based comp.	1	1	1	2	0	1	0	1	1	1	0	1	1	0
Phenol compounds	1	1	1	1	0	1	1	1	1	1	0	1	1	0
Chlorine	1	1	1	1	0	0	1	0	1	1	0	1	1	0
Veterinary medicines	1	1	0	1	0	1	1	1	1	1	1	1	1	1
Methane	2	0	1	0	0	0	0	0	0	1	1	1	1	1
Organic carbon	1	0	0	2	0	0	0	0	0	1	1	1	1	1
Hydrogen sulfide,	1	1	1	2	0	0	1	1	1	1	1	1	1	1
Carbon monoxide,	2	0	1	0	0	0	0	0	1	1	1	1	1	1
Benzene,	1	1	1	2	0	1	1	1	2	0	0	0	1	0
Toluene,	1	1	1	2	0	1	1	1	2	0	0	0	1	0
Ethylbenzenes,	1	1	1	2	0	1	1	1	2	0	0	0	1	0
Xylenes,	1	1	1	2	0	1	1	1	2	0	0	0	1	0
Wood resins,	1	0	1	1	0	0	1	0	1	0	0	0	1	0
Dioxins/furans and dioxin-like	1	1	1	2	0	1	1	1	1	0	0	0	1	0
Polynuclear aromatic	2	1	1	2	0	1	1	1	1	0	0	0	1	0
Oxides of nitrogen (Nox)	0	1	1	1	0	0	2	0	1	1	1	1	1	1
Airborne particles (PM10)	0	1	2	0	0	0	1	1	1	1	1	1	1	1
Sulfur (SOx)	1	1	1	2	0	1	1	1	1	1	1	1	1	1
Heavy metals,	2	1	0	1	0	1	1	1	1	1	1	1	1	1
Hydrogen chloride,	0	0	1	0	0	0	2	1	1	0	0	0	1	0
Metal salts;	1	1	0	1	0	0	1	1	1	1	1	1	1	1
Campylobacter spp,	1	1	0	2	1	0	0	1	0	1	1	1	1	1
Salmonella spp,	1	1	1	1	1	0	0	1	0	1	1	1	1	1
Yersinia (Y enterocolitica, Y	2	1	0	1	1	0	1	1	2	1	1	1	1	1
Q fever	0	0	1	0	1	0	0	0	1	1	1	1	1	1
Bioaerosols (including fungal	1	1	1	1	1	0	1	1	1	1	1	1	1	1
Avian influenza (H5N1), avian	1	1	0	1	1	0	0	1	1	1	1	1	1	1
Newcastle	0	1	1	1	2	0	1	1	1	1	1	1	1	1
CSF	0	0	0	0	1	0	0	1	1	1	1	1	1	1
ASF	2	1	1	1	1	0	0	1	1	1	1	1	1	1
FMD	0	0	1	0	1	0	0	2	1	1	1	1	1	1
BSE	1	2	0	1	0	0	0	1	0	1	1	1	1	1
Scrapie	1	1	0	1	0	0	0	1	0	1	1	1	1	1

List of hazardous agents	Survival/elimination of hazardous agents in regard to the selected disposal method														
	Controled	Pressure rendering	Atmosferic	Biogas (off)	IVC (off)	AD (off)	PPC Land Fill	W Composting Off	Air cut/mobile Inc	Off Farm Pyre	Mass Burial	IVC on Farm	W Composting on	On farm Pyre	On farm Burial
Ammonia, ammonium	0	0	0	1	1	1	1	1	0	0	1	1	1	0	1
Quaternary ammonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iodine based comp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phenol compounds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chlorine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Veterinary medicines	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Methane	0	0	0	1	1	1	1	1	0	0	1	1	1	0	1
Organic carbon	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Hydrogen sulfide,	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Carbon monoxide,	1	0	0	0	0	0	1	0	1	1	1	0	0	1	1
Benzene,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Toluene,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Ethylbenzenes,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Xylenes,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Wood resins,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Dioxins/furans and dioxin-like	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Polynuclear aromatic	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Oxides of nitrogen (Nox)	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Airborne particles (PM10)	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Sulfur (SOx)	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Heavy metals,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Hydrogen chloride,	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Metal salts;	1	0	0	0	0	0	0	0	1	1	0	0	0	1	0
Campylobacter spp,	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1
Salmonella spp,	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1
Yersinia (Y enterocolitica, Y	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1
Q fever	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1
Bioaerosols (including fungal	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
Avian influenza (H5N1), avian	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
Newcastle	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
CSF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASF	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
FMD	0	0	0	0	0	0	1	0	0	0	1	0	0	1	1
BSE	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Scrapie	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1

List of hazardous agents	Hazards Present in the residual product														
	Controled	Pressure rendering	Atmosferic	Biogas (off)	IVC (off)	AD (off)	PPC Land Fill	W Composting Off	Air cut/mobile Inc	Off Farm Pyre	Mass Burial	IVC on Farm	W Composting on	On farm Pyre	On farm Burial
Ammonia, ammonium	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Quaternary ammonia	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Iodine based comp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phenol compounds	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chlorine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Veterinary medicines	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Methane	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Organic carbon	0	0	1	1	1	1	1	1	0	0	0	0	1	0	1
Hydrogen sulfide,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Carbon monoxide,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Benzene,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Toluene,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ethylbenzenes,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Xylenes,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wood resins,	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dioxins/furans and dioxin-like	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polynuclear aromatic	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oxides of nitrogen (Nox)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Airborne particles (PM10)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Sulfur (SOx)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Heavy metals,	1	1	1	0	0	0	0	0	1	1	0	0	0	1	0
Hydrogen chloride,	0	0	0	0	0	0	0	0	0		0	0	0	0	0
Metal salts;	1	1	1	0	0	0	0	0	1	1	0	0	0	1	0
Campylobacter spp,	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
Salmonella spp,	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
Yersinia (Y enterocolitica, Y	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
Q fever	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
Bioaerosols (including fungal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Avian influenza (H5N1), avian	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
Newcastle	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
CSF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASF	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FMD	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1
BSE	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Scrapie	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1

Table 5.1 The input spreadsheet used in the model

[Key] The left column contains the list of hazards considered for the assessment; the upper row describes the characteristics of the hazardous agents and their presence/Absence, 1 and 0 respectively, in the considered sources (a third class, 2 is used to describe a hazard for which information is limited for a characterisation thus it characterises the hazard as present, however flagging uncertainty in that judgement.

Environmental release of hazards triggers the interaction between the hazards and the environment. Successful exposure depends on the characteristics of the hazard being able to overcome all the barriers considered for the pathways, these are represented as a succession of open/close or succeed/fail functions.

5.2.4 Process

The model was coded as macros written in Visual Basic for Applications, for use within Microsoft® Excel (Office'2007). Once the input information is complete, the program is executed directly through the macros. 35 worksheets are contained in the workbook:

Hazards process: This first sheet documents all available data in literature supporting the hazardous agent profiles. This is used to justify the assumptions applied for hazard characteristics, to ensure transparency and allow the model to be updated and revised (OIE, 2011c; Stirling and Scoones, 2009; Ahl, 1996).

Input: Input data displayed in Table 5.1 is included in this sheet.

Output [1 – 33]: The remaining 33 worksheets display the model output. Figure 4.2 provides a map of the unit processes, many of which are common for the range of disposal options considered. The output is organised according to the data-computing sheet (Table 5.1). For each column refereeing to a stage of disposal, e.g. farm, transport, reception, all process and all residual elimination, present in the table. Each sheet includes a list of the predefined 28 pathways (Table 5.2 and Table 5.3). These are represented by their abbreviations on the left column; the key for pathways abbreviations is available in Table 4.2. Following the abbreviated name is the list of hazardous agents present at the end of that particular pathway.

5.2.5 Output

Clear communication of results is a critical requirement if the project is to be successful, as poor engagement with decision makers can result in misinterpretation or even dismissal of the results. To better inform risk managers, a broader context of the decision to be made must be appreciated to convey how uncertainties and weaknesses in the assessment may influence stakeholder perceptions (Thompson and Bloom, 2000). The output produced by this model is complementary to that presented in Chapter 4 (Delgado et al., 2010). Therefore, the format of the output reflects the Pareto charts developed previously to improve communication, complementing for each pathway assessed an enumeration of the hazards at risk of exposure. Therefore discussion of the results will include those presented here (Table 5.2 and 5.3) and those presented in Chapter 4 (Figure 4.4)

5.3 Results and discussion

The results presented in this paper follow the framework and output presented in the Chapter 4 (Delgado et al., 2010). Therefore, one table, as exemplified by Table 5.2 and Table 5.3, was produced for each of the 35 Pareto charts representing a disposal stage. Each disposal stage considers the same list of exposure pathways included in Table 4.2. The result is a list displaying the hazards present at the end of each exposure pathway in a particular disposal stage for a specific disposal option. An example of the results is shown for the disposal option off-farm mass pyres code 4b (in Figure 4.2), with Table 5.2 presenting the on premises stage and Table 5.3 the processing stage.

Pathways	Hazardous Agents																	
Groundwater																		
GWconsAnim	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	ASF							
GWcropcons	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy													
GWdirect	Ammonia,	Quaternary	Phenol	Chlorine	Veterinary	Hydrogen	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols							
GWfishShell	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	ASF							
GWingestion	Ammonia,	Quaternary	Iodine based	Phenol	Veterinary	Hydrogen	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	ASF	BSE	Scrapie	
GWinhalation	Ammonia,	Quaternary	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Carbon	Sulfur	Heavy	Metal	Yersinia (Y	Bioaerosols	Avian	ASF			
GWinhalirrig	Ammonia,	Quaternary	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Carbon	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Avian	ASF			
Above Ground																		
AGdepocons	Ammonia,	Quaternary	Iodine based	Phenol	Hydrogen	Airborne	Sulfur (SOx)	Salmonella	Bioaerosols	Newcastle	ASF	FMD						
AGdirect	Ammonia,	Quaternary	Phenol	Chlorine	Hydrogen	Oxides of	Airborne	Sulfur (SOx)	Bioaerosols	Newcastle								
Agingest	Ammonia,	Quaternary	Iodine based	Phenol	Hydrogen	Airborne	Sulfur (SOx)	Salmonella	Bioaerosols	Newcastle	ASF	FMD						
Aginhale	Ammonia,	Quaternary	Iodine based	Phenol	Chlorine	Hydrogen	Carbon	Oxides of	Airborne	Sulfur (SOx)	Q fever	Bioaerosols	Newcastle	ASF	FMD			
Agwildcons	Iodine based	Phenol	Sulfur (SOx)	Salmonella	Bioaerosols	Newcastle	ASF	FMD										
AGwildspread	Q fever	Bioaerosols	Bioaerosols	Newcastle	Newcastle	ASF	FMD											
Surface-water																		
SWconsAnim	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF						
SWcropcons	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy													
SWdirect	Ammonia,	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Newcastle					
SWfishShell	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF						
SWingestion	Ammonia,	Iodine based	Phenol	Veterinary	Hydrogen	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF	BSE	Scrapie
SWinhalation	Ammonia,	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF		
SWinhalirrig	Ammonia,	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF		
SWlaeching	Ammonia,	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	ASF	BSE	Scrapie	
Ground to Surface																		
GSconsAnim	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF						
GScropcons	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy													
GSdirect	Ammonia,	Quaternary	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Newcastle					
GSfishShell	Iodine based	Phenol	Veterinary	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF						
GSingestion	Ammonia,	Quaternary	Iodine based	Phenol	Veterinary	Hydrogen	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF	BSE	Scrapie
GSinhalation	Ammonia,	Quaternary	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF		
GSinhalirrig	Ammonia,	Quaternary	Iodine based	Phenol	Chlorine	Veterinary	Hydrogen	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols	Avian	Newcastle	ASF		

Table 5.2 Risk assessment of the on-farm stage for disposal option 4b) off-farm mass pyres

[Key] Each row represents an exposure pathway, abbreviation of the name on the left followed by the hazardous agents released. Uncertainty, characterised by 2 in Table 5.1, in the results is highlighted (Grey). For the abbreviated reference of each pathway, see Table 4.2.

Pathways	Hazardous Agents																	
Groundwater																		
GWconsAnim	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
GWcropcons	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy									
GWdirect	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols				
GWfishShell	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
GWingestion	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	BSE	Scrapie	
GWinhalation	Veterinary	Hydrogen	Carbon	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
GWinhalirrig	Veterinary	Hydrogen	Carbon	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
Above Ground																		
AGdepocons	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Airborne	Sulfur (SOx)	Hydrogen	Salmonella	Bioaerosols						
AGdirect	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Oxides of	Airborne	Sulfur (SOx)	Hydrogen	Bioaerosols					
AGingest	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Airborne	Sulfur (SOx)	Hydrogen	Salmonella	Bioaerosols						
AGinhale	Hydrogen	Carbon	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Oxides of	Airborne	Sulfur (SOx)	Hydrogen	Q fever	Bioaerosols			
AGwildcons	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Salmonella	Bioaerosols									
AGwildspread	Q fever	Bioaerosols	Bioaerosols															
Surface-water																		
SWconsAnim	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
SWcropcons	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy									
SWdirect	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
SWfishShell	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
SWingestion	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	BSE	Scrapie
SWinhalation	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
SWinhalirrig	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Oxides of	Airborne	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
SWlaeching	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	BSE	Scrapie	
Ground to Surface																		
GSconsAnim	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
GScropcons	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy									
GSdirect	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
GSfishShell	Veterinary	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Campylobact	Salmonella	Yersinia (Y	Bioaerosols					
GSingestion	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Dioxins/furan	Polynuclear	Sulfur (SOx)	Heavy	Metal salts;	Campylobact	Salmonella	Yersinia (Y	Bioaerosols	BSE	Scrapie	
GSinhalation	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			
GSinhalirrig	Veterinary	Hydrogen	Benzene,	Toluene,	Ethylbenzene	Xylenes,	Wood resins,	Dioxins/furan	Polynuclear	Oxides of	Sulfur (SOx)	Heavy	Metal salts;	Yersinia (Y	Bioaerosols			

Table 5.3 Risk assessment of the processing stage for disposal option 4b) off-farm mass pyre

[Key] Each row represents an exposure pathway, abbreviation of the name on the left followed by the hazardous agents released. Uncertainty, characterised by 2 in Table 5.1, in the results is highlighted (Grey). For the abbreviated reference of each pathway, see Table 4.2.

The work developed by Delgado et al. (2010) identifies that off-farm mass pyres are the disposal option posing the highest risk of environmental contamination. Figure 4.4 displays a Pareto analysis of all five stages of disposal. The riskiest stages of disposal refer to the on-premises and the processing activities, which are represented in the Pareto analysis by Figure 4.4 a) and 4.4 d) respectively. These are corresponded by Table 5.2 and Table 5.3 respectively. For example, in Figure 4.4 a) (Chapter 4) the highest ranking pathway of exposure is ingestion of groundwater (GW ing - see Table 4.2). Table 5.2 enumerates the hazards that are likely to be exposed by that pathways of exposure, including hazards, such as ammonia, chlorine heavy metals, Yersinia. All pathways of exposure considered for the stages of disposal are represented in both Pareto charts and tables provided in this chapter.

Focussing on the results, the on-premises activities are dominated by the contamination of surface and groundwater. The agents exposed through these pathways are enumerated in Table 5.2. Agents identified are associated with cleansing and disinfection (C&D) activities, e.g. ammonia, chlorine and iodine, organic compounds, e.g. hydrogen and nitrogen sulphide, and potential release of pathogens, e.g. *Salmonella spp* and *Yersinia spp*. These results are in line with previous reports regarding the contamination of water resulting from the disposal of carcass. Here we highlight the contribution of overspill of C&D products and manure in high impact contamination events recorded during the FMD crisis in 2001 (EA, 2001). In contrast, the analysis of the processing stage enumerates a different of set of hazardous agents (Table 5.3). During this stage surface water and air contamination dominate. Air contamination is associated with fly ash (PM10), resulting from the large quantities of ash produced by animal pyres and products of combustion (PCB and PAH) (Lowles et al., 2002).

Surface-water contamination from animal pyres acknowledges the possible run-off of fuel (benzene and toluene) and heavy metals, as well as organic compounds.

5.3.1 Exploratory study

The work presented in this chapter focused on increasing the quality and quantity of data available for making decisions regarding the safe disposal of carcasses in the event on an exotic animal disease outbreak. The previous model addressed gaps in literature regarding the environmental and health impacts resulting from the disposal of animal carcasses and furthered the existing knowledge (Delgado et al., 2010). Moreover, it moved from a conventional qualitative approach to RA development, presenting a comprehensive template based on semi-quantitative judgements (Delgado et al., 2010). The format used to communicate the output progresses communication from one dimensional communication tools, such as ranking lists and risk descriptors (Pollard et al., 2008a; DH, 2001), to a more comprehensive tool providing information in sequences. The format for communicating outputs includes: (i) a higher level aimed at defining priorities across all disposal options, *distribution* of risk; and (ii) a detailed level aimed at identifying the critical control points within a specific unit process, *contribution* to risk. The model provided the template to select between disposal options with regard to their potential impact and provided the information necessary to improve future implementation of chosen disposal options. Here those findings were complemented by describing the list of hazards released at the end of each exposure pathway. This represents the next step in furthering the available information on safe disposal of animal carcasses, by identifying the hazards released at the end of each pathway, providing context to exposure.

The method presented here addresses the limited research evidence available on carcass disposal activities, by acknowledging where information is lacking (highlighted as grey in the output), developing a framework that allows selecting experts with a narrow but specific backgrounds and provides the opportunity to update the input data as new information becomes available. The advantage of object-oriented methods is the reduction in volume of input data, thus improving efficiency by reducing the burden put to experts in comparison to conventional RA templates (Pollard et al., 2008a; DH, 2001; Delgado et al., 2010) and reducing the time and resources necessary to develop a comprehensive assessment. A further advantage of adopting an object-oriented methodology is flexibility, which is the capacity to update the output, as new relevant information is available (Ahl, 1996). For example, new insight on hazardous agents, disposal options performance and changes in disposal policy. The object-oriented method allows for updating the existing hazard profiles and for adding new ones, thus allowing updates to the model as new information becomes available. Flexibility allows for a gradual increase in efficiency and accuracy of the output as new information arises.

The application of two risk assessments to produce one single output is unconventional but necessary to complete the existing information. This was made possible by the adopted object oriented methodology. The development of the model, considering the same framework allowed generating a synergetic communication process, uniting the models and resulting in an improved understanding of the drivers of exposure across the disposal chain. The development of these two models generated information regarding an area of knowledge where information is scarce. Through the culmination of both models, the existing body of knowledge moved from understanding a fraction of the risks associated with the available disposal options, to a structured body of information that enables the selection from a full range of disposal options and improving them in order to minimise the risk to the environment and human and animal populations.

Decision-making has changed alongside the ease with which information becomes available to the general public and media. Standing examples are the 2001 foot and mouth disease outbreak or the more recent HPAI outbreaks (BBC News, 2001; BBC News, 2008; BBC News, 2007). This means decisions are scrutinised by the media, increasing the need for swift and accurate decision making. Therefore, policy makers have a vested interest in being presented with complete knowledge when dealing with an animal disease outbreak or when revising emergency and preparedness plans, to ensure that the adequate controls are in place. Nonetheless, the current economic climate may limit the resources available to perform studies that support decisions, e.g. the planned cuts to Defra budget (Alistair, 2010; BBC News, 2010). Furthermore, governmental emergency guidelines and emergency response plans, although updated and revised systematically, are tested sporadically when animal disease outbreaks occur. Therefore, risk assessments play a signification role in testing those controls to ensure a safe and effective response in time of crisis.

The model produced an extensive output, where the tables presented in this paper represent a fraction of it (Table 5.2 and Table 5.3). To the authors' knowledge, the two models combined present a new perspective over the carcass disposal process, contributing to expanding the available literature. Nonetheless, the model does present limitations, which in part result from the qualitative nature of the assessment. This reflects in the models inability to provide an estimate of the quantities of hazardous agents released by each exposure pathway. However, providing quantitative outputs involves a site-specific approach that considers the number of carcass disposed of, their composition and state of decay, soil composition, topography and existing fauna, thus relying on information that may not be available in literature. Moreover, such an approach compromises the generic approach adopted, with increase costs in time and resources. Most importantly, the combined application of distinct expert based models, using independent sets of experts makes impossible to ensure consistency over the assumptions and rationale used. This approach can produce contextual inconsistencies between models, which affect the quality of the output. Therefore, the presented set-up, using combined models is a solution of recourse and future work must consider recording expert assumptions and rationale in a fashion that allows its inclusion as integral part of the output. Nonetheless, the combined models provide general guidelines for improving the currently available options for disposal of infected animal carcasses. In doing so supports swift and informed decisions made to minimise the chances of unforeseen consequences.

5.4 Conclusions

The model presented here progresses the use of expert knowledge and computer-based modelling alongside the information available for disposing infected animal carcasses. To the author's knowledge, combining two models in this way is a unique approach to understanding the issue of carcass disposal, resulting in significant improvement to the information base available. The model presented here:

- Represents an exploratory effort to improve the efficiency in the use of expert knowledge, through the use of computer-based modelling in combination with profiles that characterise hazardous agent behaviour and environmental releases.

- Complements the output presented in Chapter 4 (Delgado et al., 2010), by adding an extra tier of information, which describes the hazardous agents release through the assessed exposure pathways, thus providing context to the semi-quantitative output (Delgado et al., 2010).
- In combination with the model presented in Chapter 4 (Delgado et al. 2010), this model allows the analysis of the disposal activities through a progressively more detailed perspective. A first tier ranks the stages of disposal that pose the greater risk and a second tier identifies the riskiest exposure pathways within each disposal stage. Lastly, a third tier identifies the hazardous agents released by each exposure pathway, providing contextual of the events driving risk.
- This research highlights the need to ensure that qualitative risk assessments communicating risk hierarchies through simple ranking scales capture and communicate the rationale and assumptions supporting the rankings produced. Its inclusion as an integral part of the output adds transparency (Ahl, 1996) and can provide information useful for developing policies and risk strategies.

5.5 SUMARY OF THE FINDINGS FOR THE POST-OUTBREAK (POST T_2) PHASE

The research presented in Part 1 of this thesis, develops a comprehensive analysis of exposure associated with the disposal of carcasses during the post-outbreak (post t_2) phase of an EAD outbreak. The research applies a model based on the work develop by Pollard et al. (2008). Here, model application is improved to ensure an analysis of all pathways of exposure thus considering pathways of exposure excluded for assessments in the prior art (Section 2.2). Specifically, it focuses on the identification of activities and pathways presenting a significant risk exposure and in expanding the current understanding of system behaviour. Claims of novelty presented within these chapters are associated with insights gained and vulnerabilities identified to support policy interventions in carcass disposal activities (Chapter 4 and 5). Whilst, claims of novelty associated with the application of systemic models are discussed further in Chapter 11.

The comprehensive analysis of carcass disposal activities generated new insights that resulted in the identification of the cause of exposure. An analysis of the outputs suggests the following:

- The systemic model expands the quantity of data available, by analysing disposal options and disposal activities excluded in the analysis available in the prior art.
- Form all the disposal options and disposal activities analysed, exposure from carcass disposal activities (Figure 4.3) is most likely to result from uncontained reception and processing of carcasses, and activities perform on farm (culling of livestock).

- The model identifies the pathways of exposure and hazardous agents contributing the most to exposure for each stage of disposal (Figure 4.4, Figure 4.5, Table 5.2 and Table 5.3). Thus, it provides insights to support informed policy interventions that focus on an efficient use of the available resources.

This research adopts a new format to communicate output (Section 5.3). Communication of the outputs follows a format composed of a sequence of progressively more detailed analysis of the system. A first analysis compares the contribution to exposure presented by the different disposal activities (Figure 4.2) and a second analysis identifies the pathways of exposure associated with disposal activities, presenting CCP for efficient intervention in the system (Figure 4.4 and Figure 4.5). Lastly, a third analysis describes the hazardous agents associated with the CCP to provide information regarding the causes for barrier failure (Table 5.2 and Table 5.3). This format of communication provides access, for the first time to risk analysts and policy makers to the full range of disposal options and causes of exposure associated with them. Thus, allowing priorities to be set and policy interventions defined better.

The research presented in Chapter 4 and 5 develops a comprehensive analysis of the mechanisms of exposure and preventative controls associated with the exposure of livestock to hazardous agents. The insights generated by this research expand the knowledge available to support policy decision, reducing the gaps in knowledge associated with literature from past outbreaks (Section 2.1.2) and predictive models available in the prior art (Section 2.4). Furthermore, the research has successfully generated insight on the knowledge gaps associated with the research objectives presented in Section 2.6 (Chapter 4 and 5). The information, now available to risk analysts and policy makers provides insights to improve the existing protocols and policies associated with the disposal of carcasses.

The research developed provides added insights on the development of systemic models. Work presented in Chapter 5 addresses the limitations of the systemic model (Chapter 4). The outputs produced provide context to the numerical rankings, improving the insights available to risk analysts and policy makers to support policy interventions. Nonetheless, the approach used – a combination of two models – presents vulnerabilities:

- Application of distinct expert based models, using independent sets of experts make it impossible to ensure consistency over the assumptions and rationale used. This approach can produce contextual inconsistencies between models, which affect the quality of the outputs (Section 5.3.1).

Therefore, the presented set-up, using combined models is a solution of recourse and future applications of systemic models to EAD must consider improving recordings expert assumptions and rationale, to present as an integral part of the output.

PART 2 –SYSTEMIC ANALYSIS OF THE PRE-OUTBREAK (PRE t_0) PHASE

Part 2 involves the experimental development of an expert-based systemic model to inform on the events creating opportunities for the introduction of EADs into the UK. Model development follows the need expressed by the Defra to improve the current understanding of the drivers of exposure associated with the introduction of EAD into the UK. Specifically, it addresses the Recommendation 21 of the Risk Pathways and Countermeasures report (Defra 2011a), which states "*analysis of risks from low/medium probability risk pathways (…) to identify and assess potential (...) scenarios (if a sequence of low probability events occur), taking into account current levels of risk*" . Model development adopts an approach that enables identification of all pathways of exposure, this includes pathways identified in past outbreak alongside currently undetected pathways. This involves departing from conventional methods used to develop risk assessment models, which rely of information from past outbreak to select the pathways of exposure considered and instead adopt a method that generates those pathways of exposure, which have yet to be identified and compares them against known ones. The expert-based systemic model develops a comprehensive analysis of the source-pathway-receptor relation associated with the pre t_0 phase of an EAD outbreak. It improves the existing understanding on the available pathways of exposure and through it, presents the opportunities for improving the efficiency of the system of controls preventing the exposure of livestock to an EAD agent.

The development of the expert-based systemic model draws support from a TAG, composed of experts in EAD and policy advisors, and from the modelling insights acquired through the development of the model to study the post t_2 phase of an EAD outbreak, particularly the use of context (Chapter 5). This helped to steer the development of a transparent and logical method, which provides an effective decision support tool. A caveat of this approach is the requirement to model each disease agent independently and therefore this study includes two applications to modelling the incursions of CSF and FMD. This characteristic however, provides the opportunity to compare the outputs. This model produces a comprehensive analysis of the drivers of risk associated with the pre t_0 phase, providing information to support decisions that aim to improve UK resilience against future EAD outbreaks.

Part 2 includes the description of a novel method to develop a systemic assessment of the mechanisms responsible for the introduction an EAD into the UK and to identify vulnerabilities in the preventative controls in place (Chapter 6). This chapter also includes a discussion of its advances in comparison with the prior art, and critique of its use to support policy decisions. A second methodological section describes the approach developed to retrieve expert opinions (Chapter 7). A first application of the method to study CSF is presented in Chapter 8. This chapter includes an extensive analysis of the outputs, resulting in the development of a comprehensive analysis of the system and concludes with a discussion of its contribution to expand the quality and quantity of information now available to risk analysts and policy makers (Section 2.7). A second application to study FMD focus on improving method application based on comments from the TAG meeting (Chapter 9). Similarly, this chapter includes an extensive analysis of the output, and discussion of the insights gained. The insights generated from both applications (CSF and FMD) are analysed further to detect trends in vulnerabilities and to analyse the influence of low probability events (LEP) in UK's vulnerability to EAD (Chapter 10). This chapter includes comments on the best approach to control LPE. A summary of the findings produced by the research presented in Part 2 is presented in Section 10.7.

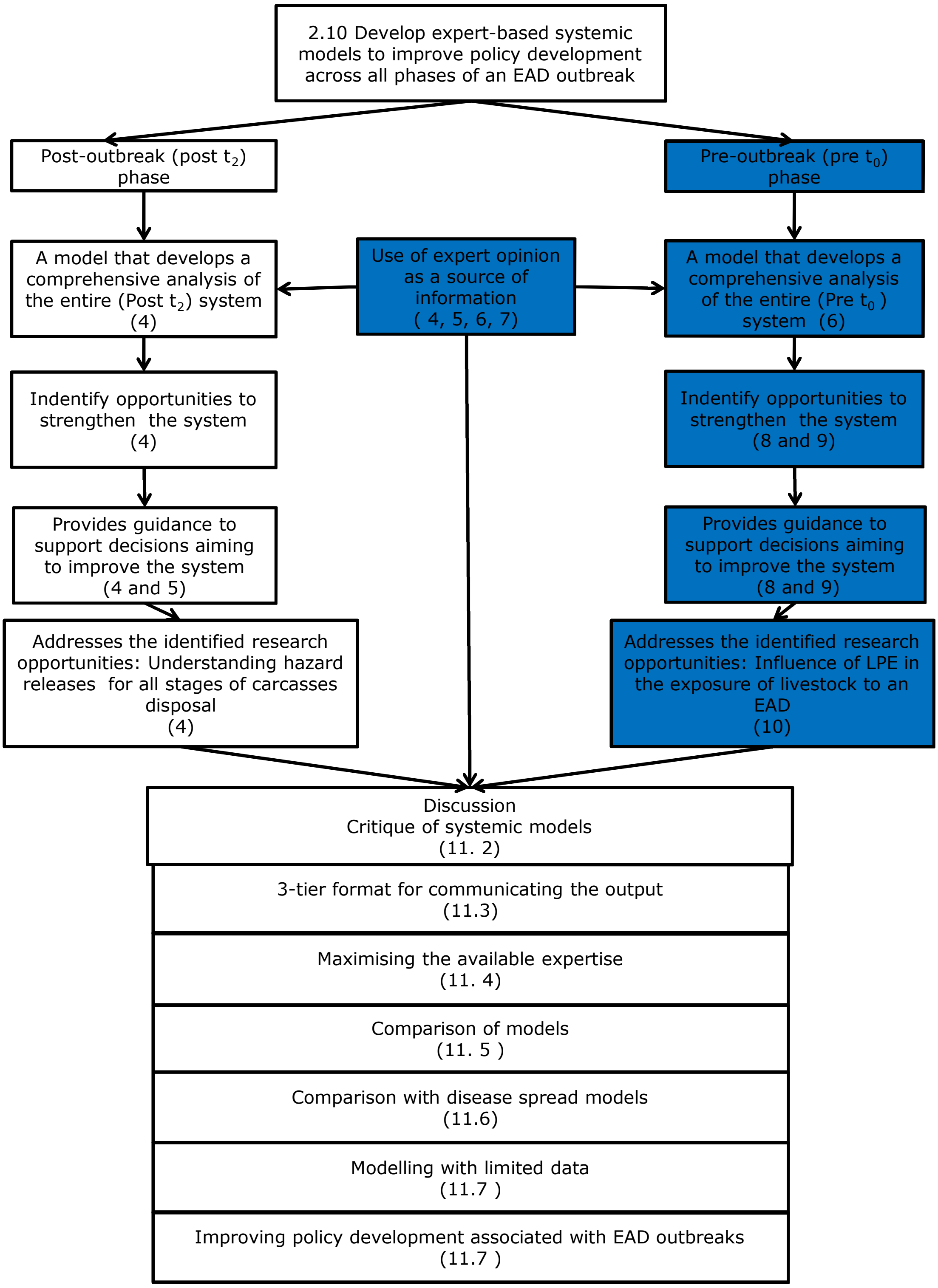

Figure 5.0.1 Part 2- Systemic analysis of the pre outbreak (Pre t_0) phase

[Key] The blue boxes display research objectives of the experiment. Numbers display the chapters

6 A SYSTEMS APPROACH TO THE RISK ANALYSIS OF EXOTIC ANIMAL DISEASE I: CRITIQUE OF METHODS AND NETWORK MODEL DESCRIPTION

This chapter presents the method to develop a systemic analysis of the UK's vulnerabilities to an incursion of an exotic animal disease. Here, the method and modelling approach are described in detail. Furthermore, the methods theoretical advantages and disadvantages are discussed in comparison with the methods conventionally used to study risk of disease introduction.

> Submitted to Risk Analysis Journal:
> Delgado, J., Pollard, S.T.J., Snary, E., Black, E, Prpich, G., Longhurst, P., "A systems approach to the policy level risk assessment of exotic animal disease: network model and application to classical swine fever" (Submitted to Risk Analysis Journal on 24 January 2012).

6.1 Introduction

Expanding free markets and unmitigated globalisation have increased countries' exposure to exotic animal disease (EAD). Prevention of EAD incursion is complex and requires the dynamic management of potential entry points, pathways and preventative barriers. Understanding the interactions between these is a focus for governments managing the risks of EAD (Defra, 2011a). Conventionally, risk assessments (RAs) have been used to assess the risk and impact of an EAD in a specific time and place, and inform management practice (Defra, 2011c; Taylor, 2003). Both qualitative and quantitative risk assessment methods have been employed. However, in the search for a comprehensive picture of systemic knowledge of disease incursions, these approaches are often limited. Here, we evaluate the current methods for assessing the risk of exposure to an EADs and offer an analysis of the merits and limitations of established tools. Building on this, we present an alternative method aimed at improving EAD risk assessments that are specifically required at the policy level. The proposed framework assesses the risk of incursion at various critical control points (CCP) across a country's disease management plan and has been developed within the context of EAD protection within the UK.

6.1.1 Exotic animal diseases

EADs are transboundary hazards, owing to the capacity to spread substantial distances and cause a significant impact (e.g. direct and indirect economic loss to farmers and governments) on a local, national and international level (Otte et al., 2004; Morgan and Prakash, 2006). The concern over transboundary animal diseases is long-established and exacerbated by the intensification of the agricultural sector and the expansion of global markets. Recent examples of EADs in the UK include the 2001 and 2007 foot and mouth disease (FMD) and 2000 classic swine fever (CSF) outbreaks (Anderson, 2002; Gibbens et al., 2000; Sharpe et al., 2001; Scudamore, 2002; Anderson, 2008), while avian influenza (AI) and the bluetongue (BT) pandemics represent international examples (Defra, 2007c; Thiry et al., 2006; Defra, 2008c). The prevention of EADs provides extensive economic benefit, and developed countries expend considerable effort in preventing and mitigating EADs to maintain an economically favourable 'disease-free' status (WHO/FAO/OIE, 2004), much of this devised at the policy level and requiring intimate knowledge of systemic risk and its reduction. The threat of an EAD incursion is relentless, requiring governments to maintain vigilant management practice. Interaction between the pathways of introduction, multiple stages of exposure, subsequent impacts and barriers of management are highly complex. Management therefore requires a broad understanding of the systemic risks, at a policy level, in order to derive cost-effective programmes adapted to high-level protection and national preparedness (Otte et al., 2004; WHO/FAO/OIE, 2004). This contrasts with the bulk of risk assessment practice that, to date, has focused on analysing the trajectory and consequences of specific outbreaks.

6.1.2 The UK multi-barrier defence system and failure to prevent outbreak

The UK framework for the prevention and control of exotic animal diseases integrates the combined efforts of multiple government agencies (e.g. local authorities, Animal Health Agency, Meat and Hygiene Service, HM Revenue and Customs and the UK Borders Agency (Defra, 2011a)), each of which holds specific management roles and responsibilities. Mutually independent, the functions provided by these agencies create a complex network of distinct protection barriers that operate as a whole system. Described as a ‘multi-barrier system’, imbedded redundancies protect against the inherent imperfections of even the most effective barriers in place (Reason, 1997). The system acknowledges the occurrence of rare events that may compromise barrier efficacy and it guards against situations where a single barrier failure may lead to a disease outbreak. However, system failures do still occur, and may be due to a rare coincidence of successive failures in multiple defences, which creates pathways for hazardous agents to reach susceptible animals. The more robust the defence network, the more unlikely an incursion is. Nonetheless, incursion is always theoretically possible (Reason, 1997), which is why understanding the complexity of the system is vital for the development of effective and risk-informed management systems (Morris, 1995).

6.1.3 Key issues for improving prevention of exotic animal diseases

EAD outbreaks result from complex interactions between the host, the disease agent, and environmental conditions (e.g. human activities) (Kuiken et al., 2005). Understanding the role each of these aspects plays is central to identifying any weaknesses in the management system (Morris, 1995). The introduction of an EAD is influenced by a disease agents' unique characteristics influencing the route of import (for a summary of transmission mechanisms see the Royal Society's report "Infectious Disease in Livestock" (The Royal Society, 2002)) and the complexity of interactions between the environment, hosts (e.g. wildlife and livestock), trade routes, and the level of biosecurity provided by animal production systems (e.g. extensive vs. intensive). This complexity generates a large number of possible release and exposure pathways (Morris, 1995). Though multi-barrier systems harbour some redundancy that could improve protection, the efficacy of these systems remains vulnerable to human factors (Reason, 1997; Kuiken et al., 2005; Reinach and Viale, 2006). Improving these systems is difficult as evidenced by the investigation of past outbreaks, which are frequently inconclusive on root causes (Defra, 2010b; OIE, 2010) (Figure 6.1). Consequentially, true system failures are difficult to detect and therefore performance levels for controls are poorly documented (Wieland et al., 2011; Defra, 2010b). Understanding the relationship between opportunities for transmission provided by EAD characteristics and environmental complexity against the efficiency of risk management controls is therefore central to enhancing the national level of preparedness.

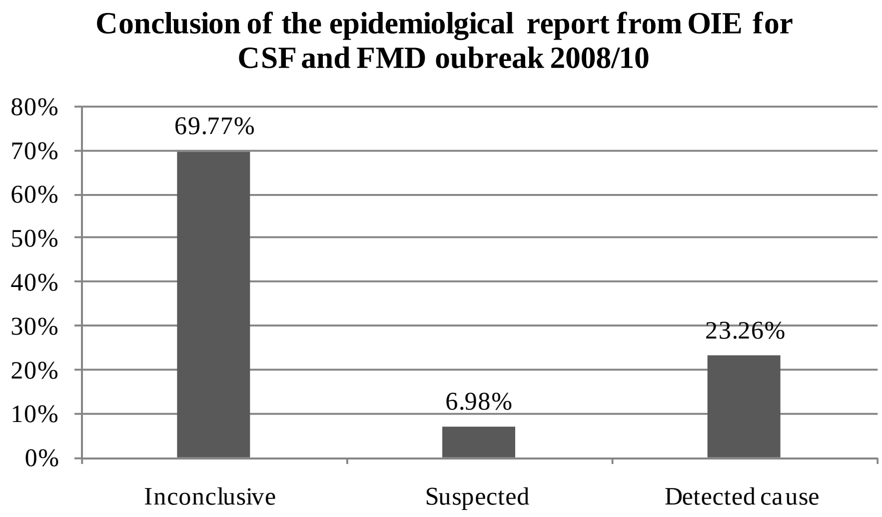

Figure 6.1 Analysis of the epidemiological reports develop by the OIE (2010) for CSF and FMD outbreaks from 2008 up to 2010 according to the success or failure to detect the responsible pathways of introduction

6.1.4 Import risk assessments

Import risk assessments (IRA) are used to assess the likelihood and consequence of an EAD incursion, usually at a specific location in space and time. The objective of the IRA is to gain further understanding of the likelihood of a disease incursion, say to a specific pig herd, and the interactions between a disease agent and the protection system. Guided by international standards (OIE, 2011c; Taylor, 2003; Murray, 2002), IRAs employ a range of qualitative and quantitative risk assessment methods, depending upon the objective and context of the decision at hand. Table 6.1 presents a summary of conventional approaches to IRA, along with an evaluation of their respective strengths and weaknesses. The methods employed are well established. However, we argue they have lesser value when applied at the policy level and, in the context of increased system complexity, may fail to provide a systematic analysis of all the introduction mechanisms, and so the subsequent threat of EAD releases.

Advantages	Disadvantages
Expert-based qualitative model	
Time (enables quick assessments and are adequate to find solution in times of crisis)	Repeatability and validation
Cost (do not require specialist software)	Results are presented in descriptive terms (high, medium and low), low level detail of the output
Use all types of data, thus overcoming data limitations in the research literature	Comparative output
Application to complex open systems	Sensitivity analysis cannot be applied
Scenario-based quantitative model	
Event-tree based models: detail analysis of pathways of exposure and exposure mechanisms	Extensive prior knowledge to select pathways to be assessed
Binomial probability model	Cost and time
In stochastic models, a value for variable uncertainty and/or variability is provided	Data availability (data is not always available and assumptions have to be made, that undermine the value and validity of the model
Repeatability, auditable, and validation	
Sensitivity analysis is applicable	
Data can be updated to account for changes in the system represented	
Model for total system analysis	
Capacity to study large system, represented through the use of an interaction matrix	Repeatability and validation
Use all types of data, thus overcoming data limitations in the research literature	Complex process of elicitation
Results are represented as numerical values	Comparative output
Contextualization provides a descriptive insight the mechanism of disease transmission	Pathways described with an intermediate level of detail, where the multiple mechanisms of disease transmission have no influence in the
Representation of all pathways and components	It does not allow to estimate uncertainty and/or variablity
Sensitivity analysis is applicable	

Note: Difficult to validate all types of RA

Table 6.1 Description of the strengths and weaknesses of the import risk assessment (IRA) methods applied to date; comparison with total system analysis

IRA tools exist in two groups; expert-based and scenario-based. The majority of expert-based models are strictly qualitative (Peeler et al., 2006) such as those applied by

Australia and New Zealand (BioNZ, 2006). Qualitative methods rely on a process of hazard screening, identification and classification and use qualitative descriptors to assess the likelihood and severity of the impact of EAD introduction (Reed, 2009b; Reed, 2009a; AQIS, 1999; AQIS, 2000). The Department for Environment, Food and Rural Affairs (Defra) in England and Wales currently uses these techniques (Sabirovic et al., 2005; Sabirovic and Hall, 2004; Taylor et al., 2006). Qualitative methods rely on multiple sources of information, including expert opinion to develop risk descriptors and estimate risk (Defra, 2010b). Experts synthesise information from a range of possible events, often providing a single 'score' as a surrogate risk estimate. The approach is limited in its ability to capture the complexity of the system, but offers a pragmatic alternative when dealing with events where sparse data exists. This approach enables rapid assessment, allowing decision-makers to discern priorities and design management solutions in short time frames. These frameworks are suitable in times of crisis, for example during the FMD crisis of 2001. Other expert based assessments apply increasingly complex elicitation methods, such as conjoint analysis (Horst et al., 1998; Nissen and Krieter, 2003; Gallagher et al., 2002), or quantitative methods that rely on expert knowledge to support a fuller assessment. These assessments use a more complex and time-consuming elicitation process, to benefit the accuracy of the elicited values however without benefit to increased detail. As an example, Horst (1996) presented an exhaustive list of the importation, release and exposure routes, in order to prioritise them according to importance. Though extensive in analysis, the output was a ranked list of risk factors and sources that provided limited analytical depth. Expert based models are flexible enough to allow the study of large systems (Taylor, 2003; Peeler et al., 2006). Nonetheless, their highly descriptive nature may fail to provide system oversight, reveal system complexity and the full extent of resulting introduction scenarios. Scenario based modelling includes end-point quantitative models and mechanistic models which focus on describing specific disease introduction scenarios using event-trees (Singer et al., 2011). These methods require quantitative evidence to support the application of mathematical models. The complexity of the models depends upon the objectives of the analysis, with complexity increasing as analysis moves from one pathway (Yu et al., 1997; Sutmoller and Wrathall, 1997) to multiple introduction pathways (De Vos et al., 2004; Hartnett et al., 2007; Bronsvoort et al., 2008; Weng et al., 2010). Similar complexity can be expected when assessing the impacts to multiple receptors (Vose, 2008; Murray, 2002). Compared to expert-based assessments, scenario-based models provide greater diagnostic detail about the likelihood of introduction. However, this comes at the cost of extensive, time and resource consuming preparatory work and input data. These costs ultimately restrain the scale of these assessments (Vose, 2008; Murray, 2002) which produce a narrow view of a disease introduction, i.e. a small portion of all available pathways.

The consensus among the scientific community appears that the management of disease incursion using these two IRA perspectives provides an acceptable understanding of EAD importation mechanisms and associated risks (Taylor, 2003; Peeler et al., 2006). However, we need to exercise caution about the true extent of our systems understanding that we claim for. The top-down approach requires the existence of prior knowledge about the mechanisms involved in creating introduction pathways and the behaviour of system barriers (Dangerfield and Morris, 1992; Grundke, 2010).. However, for incidences such as the CSF 2000, FMD 2001 and HPAI 2007 outbreaks, Defra identified causal pathways resulting from a conjunction of unlikely events.

Assessing such pathways is beyond the scope of conventional IRA methods, as is the identification and understanding of the mechanisms involved for creating an incursion opportunity. Therefore, if conventional methods alone are used to study the risk of importing EADs, our gaps in knowledge and understanding will remain.

6.2 <u>An alternative methodology for import risk assessments</u>

We are concerned with risk assessments performed to inform and improve preventative risk management measures at the policy level, and undertaken in the absence of an active outbreak. The method below addresses some of the limitations identified above and is achieved through the identification of different pathways that may result in a susceptible receptor being exposed to an EAD. Critically, for policy level analysis, these pathways are the result of numerous interactions between system components; for example, livestock breeding, distribution and food preparation (Defra, 2011a), rather than through the linear analysis of components in an event tree. Providing an understanding of system properties and of how elements and controls interact enables us to predict behaviour better (Murthy and Krishnamurthy, 2009; Pearce and Merletti, 2006; Mitchell, 2006). To achieve this, we propose a method that integrates network system analysis with features, events and process (FEP) analysis. By combining these two approaches, we intend to expand the assessment of potential events that may trigger a barrier failure, so initiating an EAD incursion. Network analysis attempts to understand interactions between species and the environment. Examples exist in the epidemiological and disease transmission literature where this has been widely applied (Bigras-Poulin et al., 2006; Ortiz-Pelaez et al., 2006). Functionally, a network is comprised of a number of nodes and the connections that exist between them (arcs).

FEP analysis is used to define relevant exposure scenarios and has been routinely applied in the development of nuclear waste repositories and proposed for the geological storage of carbon dioxide (Freeze et al., 2005; Savage et al., 2004). In addition to expanding the study of potential introduction routes, this approach intends to unveil new interactions at play that may have been overlooked.

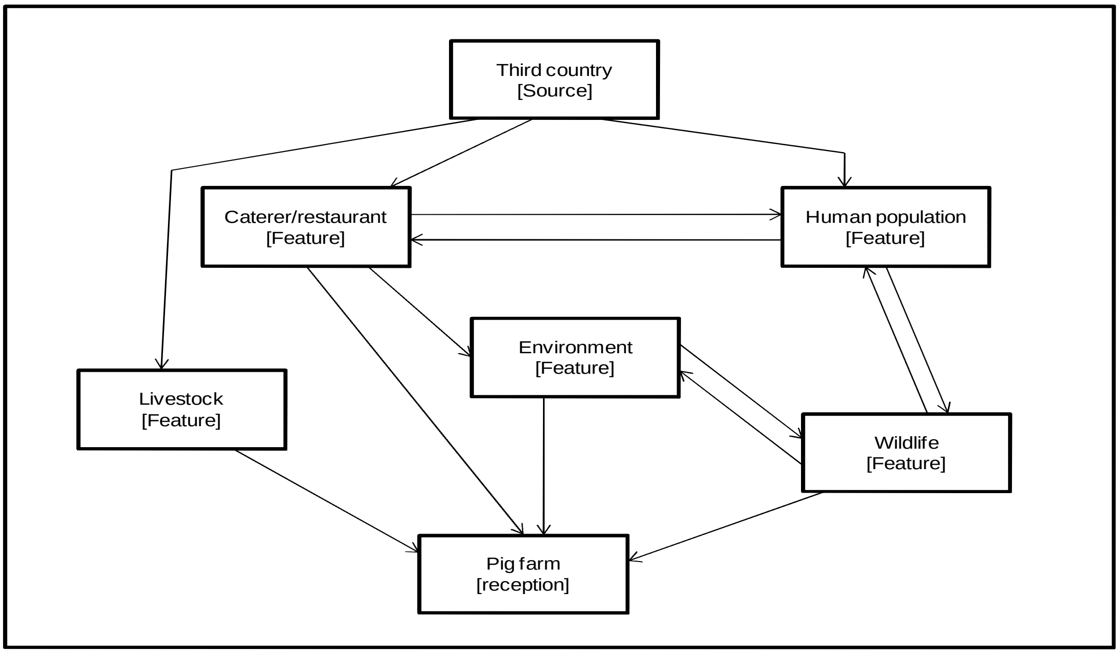

Figure 6.2 Network model of the system

[Key] Nodes represent the features; arcs represent the process. The (Node Third country) represents the disease source; (Node pig farm) represents the terminal node (terminating the simulation); the remaining nodes represent components contribution to disease transmission; and (Arcs) are represented by the arrows corresponding to movement between two adjacent nodes

6.2.1 Feature, events and processes list application to classical swine fever.

A FEP list (Savage et al., 2004) provides a set of system features, system events and system processes that when combined, generate an exposure scenario. For our purposes, 'features', the components within the system (e.g. farms, fomites, border inspection posts, and human or livestock populations) are represented as network nodes (Figure 6.2). The nodes include the source of EAD, countries without a disease free status, and receptors, e.g. livestock farms. ‘Processes’ represent the opportunities for disease transmission between adjacent nodes, and are represented in the network as arcs. Each arc represents a single process and nodes may be connected to several other nodes. The extent of connectivity between two adjacent nodes is defined as an incidence and is assigned a value. ‘Events’ are the causes of barrier failure and are not represented graphically in the network. Barrier failure does not necessarily represent disease transmission; rather it describes a situation where transmission is possible. Events are assigned a value that describes the barrier failure rate, reflecting the expert confidence in barrier efficacy. A complete FEP list is a comprehensive record of all the values attributed to each process and arc present in the network, and of all the description and assumptions associated with them.

Third country		0103	0104	0105		
	Caterer/ /restaurant	0203				
	0302	Human population			0306	
			Environment		0406	0407
				Livestock		0507
		0603	0604		Wildlife	
						Pig farm

Figure 6.3 Interaction matrix

[Key] Diagonal cells represent the nodes. Third country as source and pig farm as terminal are the start and finishing points respectively. The remainder of possible node connections [the code in the off diagonal cells marks an existing connection, records the coordinates of the movement]

6.2.2 Data collection and modelling challenges

Risk assessment favours the use of quantitative supporting data as a reliable and auditable source of information (Taylor, 2003; Peeler et al., 2006). However, for the study of incursion and exposure of EAD to susceptible receptors, such data are often sparse, incomplete and therefore unavailable in the quantities necessary to develop a comprehensive quantitative analysis of the mechanisms driving exposure (Figure 6.2). In such circumstances, expert opinion presents an alternative source of information to overcome the limitations in the research literature (Taylor, 2003; Peeler et al., 2006). The systemic model relies on expert judgements to inform the model and assign values to the FEP network. Required from the experts in this case, is an evaluation of:

Incidence: the number of times a connection is attempted, with or without successful transmission during a predefined time interval. The degree of ‘challenge’ in the system.

Barrier failure rate: the number of times a barrier fails to detect and/or eliminate a disease agent, versus the number of times a connection is attempted.

Events: a description of the events provoking barrier failure and classification according to error type - human and/or system error.

6.3 Scenario simulation, pathway calculation and system properties

The model presents an estimation of the likelihood of a pathway being available for the introduction of a disease agent into the UK. Focus is on providing a comparison between the availability of pathways for exposure (scenarios) and not in the calculating the likelihood of infection. Thus, the model takes no account of the likely prevalence of infection (or frequency of breakdown) at the sources nodes). A scenario is an imagined sequence of events; for example the sequence of events necessary to allow an EAD to come into contact with a susceptible receptor, where a receptor is an animal from susceptible species to the EAD considered, in a livestock farm. Multiple scenarios resulting in a system failure (i.e. disease incursion) may exist. We simulate these using a pre-programmed Excel™ spreadsheet that describes the network as an interaction matrix (IM; Figure 6.3). Diagonal cells represent network nodes; off-diagonal cells (where full) represent a connection between two nodes. The off-diagonal cell [i, j]; with A being row and B the column, represents the connection between the node [i, i] and the node [j, j], whereas cell [j, i] represents the inverse connection. If an off diagonal cell is empty, there is no connection between the two respective nodes. When completed, the matrix represents every possible connection within the system. Using the IM, a scenario simulation analysis (SSA) generates all possible outbreak scenarios, leading from a source node to a receptor. A direct pathway contains two nodes and one arc, whilst indirect pathways contain $\boldsymbol{n}$ nodes and ($\boldsymbol{n}$ *-1)* arcs. A pathway length $\boldsymbol{k}$ refers to the number of arcs present in the pathway ($\boldsymbol{k} = \boldsymbol{n} - \mathbf{1}$). (P) represents the likelihood of the pathway that resulted in infection. It results from the estimations of the likelihood of the sequences of transmission between any two adjacent nodes (X) considered in pathways, where $X_{(i,j)}$ is the likelihood of transmission between two random nodes within the network can be described. For direct pathways, where $k = 1$ the value of P is equal to the value of X for the source and receptor node,

$$P_{(s,r)} = X_{(s,r)} \text{ ; and} \qquad \text{(Eq. 1)}$$

for indirect pathways, where $k > 1$ P is calculated using the following equation, which considers a random sequence of adjacent connections from source to receptor node,

$$P^{*}_{(s,r)} = X_{(s,i_1)}.X_{(i_1,i_2)}.X_{(i_2,i_3)} \dots .X_{(i_{m-1},i_m)}.X_{(i_m,r)}; \qquad \text{(Eq. 2)}$$

Where, $P^*_{(s,r)}$ is the likelihood of a pathway between a source node (s) and a receptor node (r) and i represent random adjacent nodes from *n* network nodes.

Therefore, (P) depends on the likelihood of the adjacent connections. This is calculated by $X_{(i,j)}$, where i and j are any two randomly selected nodes in the network, $Ic_{(i,j)}$ represents the value for incidence associated with the process connecting nodes i and j and $BFR_{(i,j)}$ is the value for barrier failure rate.

$$X_{(i,j)} = \frac{Ic_{(i,j)}}{\sum_{c=1}^{i-1} Ic_{(i,c)} + \sum_{c=i+1}^{n} Ic_{(i,c)}} . BFR_{(i,j)} \text{ ; for } j \neq i \qquad \text{(Eq. 3)}$$

where $i = 1, \dots, n$.

The output of the model is a list of all pathways allowing exposure of susceptible receptors to the disease agent. That list includes a description of all the nodes composing the pathways and a respective likelihood (P) value.

6.3.1 Sensitivity analysis

In addition to an estimation of the likelihood on disease incursion, system vulnerability is also evaluated. System vulnerability is represented by the sum of the likelihood of all pathways. It represents the likelihood of system failure and defines a base case for system performance. The value represents a snapshot of system vulnerability to the incursion of an EAD. This value also allows the detection of which arcs and associated events promoting barrier failure pose a greater influence to overall systemic vulnerability. This can be achieved by the application of a local 'one at a time' sensitivity analysis to the model targeting the behaviour of the barriers associated with each arc (Frey and Patil, 2002; Hamby, 1995) and is valuable for identifying risk management interventions that are likely to be most effective in times of risk reduction.

6.4 Discussion

Globalisation is increasing the movement of people, goods and vehicles within and across borders while additional controls are put in place to combat new risks. The increase in system complexity is leading to unexpected interactions that generate less predictable pathways of EAD introduction. New risk assessment tools are required at the policy level to address this challenge. Though the majority of these pathways may be of low likelihood, their increasing presence poses a challenge in maintaining overall system resilience. Therefore, concern is directed towards the occurrence of a sequence of low probability system failures that may ultimately result in an incursion incident (Defra, 2011a; Reason, 1997; Pidgeon and O'Leary, 2000).

We suggest conventional risk assessment methods used successfully at the local outbreak level, are inadequate to further understanding at the policy level of the causal relationships between foreign disease sources, susceptible receptors and controls. This approach combines the information gained from expert-based and scenario based models to develop such understanding (Taylor, 2003; Peeler et al., 2006). However, it is susceptible to systemic channelling (progressive narrowing of the scope of assessment) and offers limited understanding of system behaviours. In practice, this leads to a focus on a small number of priorities, which in turn may weaken the rationale for policy intervention and risk mitigation strategies (Dangerfield and Morris, 1992; Grundke, 2010). The method offered here adopts a bottom-up approach, based on a firm belief that models emerge as a whole, and cannot be understood properly by the atomised analysis of constitutive parts (Murthy and Krishnamurthy, 2009; Zio, 2009). Bottom-up models allow the development of true systemic studies, obtained through the generation of an abstract representation of reality, presenting the following structural advantages: (Pearce, 1996; Murthy and Krishnamurthy, 2009; Pearce and Merletti, 2006; Freeze et al., 2005; Jordán and Scheuring, 2004; Newman, 2003; Zio, 2009; Scherrer et al., 2008)

a) The model is based on simple local rules that drive the complex behaviour observed at a global level, understanding the rules governing system behaviour allows for making predictions. This enables the use of the model to infer on system resilience, simulating UKs' overall resilience against a disease introduction.

b) The model allows for interplay between bottom-up and top-down perspectives through several levels of granularity, allowing the analyst to assess the effects of micro behaviour in system performance and system weaknesses and these key areas for intervention, e.g. critical control points (Delgado et al., 2010). These properties make network models particularly suited to large, complex systems where the role of each individual component is not altogether clear (Pearce and Merletti, 2006; Newman, 2003).

Here, the pathways are not dictated by the assessor prior to the assessment, but generated from within the system based on disease agent and system component interactions. This generates a very large number of introduction pathways, from which none can be excluded. In contrast with conventional approaches (OIE, 2011c; Vose, 2008; Taylor, 2003; Murray, 2002) , the model does not focus on the effects of individual pathways but produces an estimation of system behaviour based on the likelihood of all generated pathways and provides information as to the influence of components within the system (Newman, 2003). The interplay between macro and micro perspectives provided by bottom-up models allows us to examine the sensitivity of the system to the behaviours of individual components (Murthy and Krishnamurthy, 2009). The model assumes that an individual barrier failure is not exclusive to one pathway. Nonetheless, increasing control over that failure will decrease the likelihood across a number of pathways, improving system behaviour. For example, a failure (a) may provide agent access to two high likelihood pathways, and a failure (b) to thousands of low likelihood ones. Understanding which failure has greater influence on system behaviour will lead to better control decisions. The proposed sensitivity analysis enables a comparison between all components and individual barrier failures thus allowing for identification of critical control points; key areas where intervention is likely to produce higher impact (Delgado et al., 2010).

An analysis concentrating on the *features* (components) allows defining priorities at a macro level, and a second analysis focussing on the *processes/events* the identification of key areas to intervene with regard to those priorities. This provides an indication of 'where' to intervene. However as the causes of barrier failure are captured by the FEP list, it also allows provides added information on 'how' to intervene. Latent failures are a key concept when assessing a multi-barrier system, and reviews on the causes and consequences of latent barrier failures are available (Reason, 1997; Pidgeon and O'Leary, 2000; Sonnemans et al., 2010). Barrier performance is influenced by a multitude of factors, including technological and resource limitations, political and social issues (EU free market agreement), and human factors. Understanding how these influence each individual *process/event* provides insight for the development of risk mitigation strategies, if intervention is at all possible.

A key feature of our method is its flexibility, which is the capacity of the model to update input data (OIE, 2011c; Ahl, 1996). The structure provided by the FEP list and character of each process/event individually allows for updating sections of the input data without influencing the remaining system components. Updating can be performed in light of new, relevant data thus increasing the accuracy of the results. As government policies change and new intervention strategies are implemented, the ability to update is valuable for maintaining relevant political and economic context.

The models purpose contrasts with that of conventional scenario based quantitative methods in that it was developed for use on a regular basis to provide an estimation of how changes in factors exterior to the system (political economical, new outbreaks) affect behaviour. For example, Defra is compromised in developing a qualitative assessment of the risk factors associated with disease import for each new outbreak detected worldwide (Defra, 2010b). In light of the limitations presented by qualitative expert based methods in providing system overviews of the risks, we suggest application of the both models in tandem. This allows confirmation and validation of the priorities identified, and if necessary, informs on intervention strategies in short time. Furthermore, it allows for the development of a feedback loop between the two models, generating increasing accuracy of the results.

In consideration of the exploratory nature of the method developed and the scarcity of data in literature, particular attention was given here to model validation. The internal validation process was influenced by publications on IRA good practice (OIE, 2011c; Murray, 2002; Ahl, 1996). Furthermore, the method development process was closely followed by a Technical Advisory Group composed of experts from Defra, VLA and other institutions, whose role was to challenge the approach and provide alternatives to the model, improving it robustness. The model presents a number of limitations in comparison with conventional risk assessment method. For example, it focuses inwardly and does not account for disease prevalence at source. At its core the model remains an expert based-assessment and is consequentially susceptible to expert biases. We suggest to limit the application of the model into providing a comparison between the several features and process/events considered, their behaviour and influence in system behaviour; and avoid using the model, in absolute values, such as to predict the number of years between outbreaks. In spite of these limitations, this represents the first attempt to develop a model that provides a systemic perspective over the risk associated with animal disease.

6.5 conclusion

We propose a network model for the examination of systemic risks from exotic animal disease incursions at the policy level. This model complements the conventional tools adopted for IRA and allows the identification of system priorities, defining key areas of intervention for the development of risk mitigation strategies. Its flexibility allows for a constant update of input data and can be used alongside Defra's qualitative template to assess the risk of disease introduction with each new EAD outbreak, outside the UK.

6.6 Acknowledgements

We thank David Mouat, Bill Parish, Allick Simmons (Defra) and Emma Snary (VLA). JD was supported by Cranfield University and the Risk Centre. This research was part-funded by Defra, the AHVLA and a cross Council EPSRC, NERC, (ESRC) research grant (EP/G022682/1) awarded to the Risk Centre at Cranfield University.

7 THE ELICITATION PROCESS

This chapter describes in detail the elicitation method used to gather information from experts. This method of elicitation provides the data, to be inputted into the model described in Chapter 6. Applications of the method are described in Chapters 8 and 9.

7.1 <u>Introduction</u>

The method developed to study the events associated with the incursion of exotic animal diseases into the UK relies on extensive data to characterise the behaviour of the various components within the system, particularly when considering that behaviour is defined by the frequency of movements and the efficiency of the controls between nodes. Research literature is limited in providing the necessary information to run the model. Where data is unavailable, to overcome data scarcity, expert knowledge has been applied with successful results. However, the use of expert knowledge involves developing a knowledge acquisition protocol and elicitation exercises. This presents a series of challenges.

There are a variety of knowledge retrieval techniques that have been applied in previous elicitation exercises. Selecting between these depends greatly on the objective of the project and the expected output from the elicitation exercise. Selection also depends on the assessors understanding of the problem, the approach to solve it and of the assessors understanding of what composes knowledge (Compton and Jansen, 1990). Consequentially, the development of an elicitation protocol becomes a practical exercise, which is often guided by a process of trial and error.

The available literature on the practical aspects of developing a knowledge acquisition protocol is limited. Furthermore, the majority of expert based IRA fail to make explicit or even reference the technique used for elicitation (Defra, 2010b; Sabirovic and Hall, 2004), where the exception is the work developed by Horst et al. (1996). The parameters over which knowledge is elicited are specified, but the exact technique and interaction with the experts is not described. This is equally true for expert based studies applied to other fields (Compton and Jansen, 1990). Similarly, method reviews explain the nature and objective of the exercises but fail to provide a protocol for gathering expert knowledge (O'Hagan, 1998; Neale, 1988; Cooke and Goossens, 2000; Olson and Rueter, 1987).

Limitations in the number of experts and in time available with them have to be factored in (Cooke, 1994; Liou, 1992; Meyer and Booker, 2001). Such limitations play a significant role in the selection of the method, as failing to complete the proposed tasks may render the data generated useless and overburdening of experts may compromise data quality (Cooke, 1994; Cooke, 1991).

7.2 The knowledge acquisition protocol

The development of a knowledge acquisition exercise is more than a theoretical exercise and the quality of the elicitation depends greatly on the experience of the assessor and on his capacity to learn from previous failures. As the opportunity for trial and error with an expert panel was absent, the techniques selected focus on ensuring that an eight hour workshop was sufficient to provide all the necessary data to run the model. Unfortunately, the impact of such decisions resulted in discarding complex methods of elicitation, such as a Delphi, delft or conjoint techniques in favour of a more simplistic yet time efficient methods (Horst et al., 1998; Brown, 1968; Cooke and Goossens, 2008).

The knowledge acquisition protocol is represented in Figure 7.1. The protocol includes two stages of elicitation. The first stage focuses on selecting the components of the network to be considered, an activity performed in preparation to the workshop. The second stage of the process involves characterising the behaviour of the individual components. This was the central activity of the elicitation workshop. The development of the elicitation exercises was influenced by the procedure guide for structured expert judgment development by Cooke and Goossens (2000), with expert selection based in domain expertise, experience and availability (Liou, 1992). A detailed display of the elicitation procedures follows:

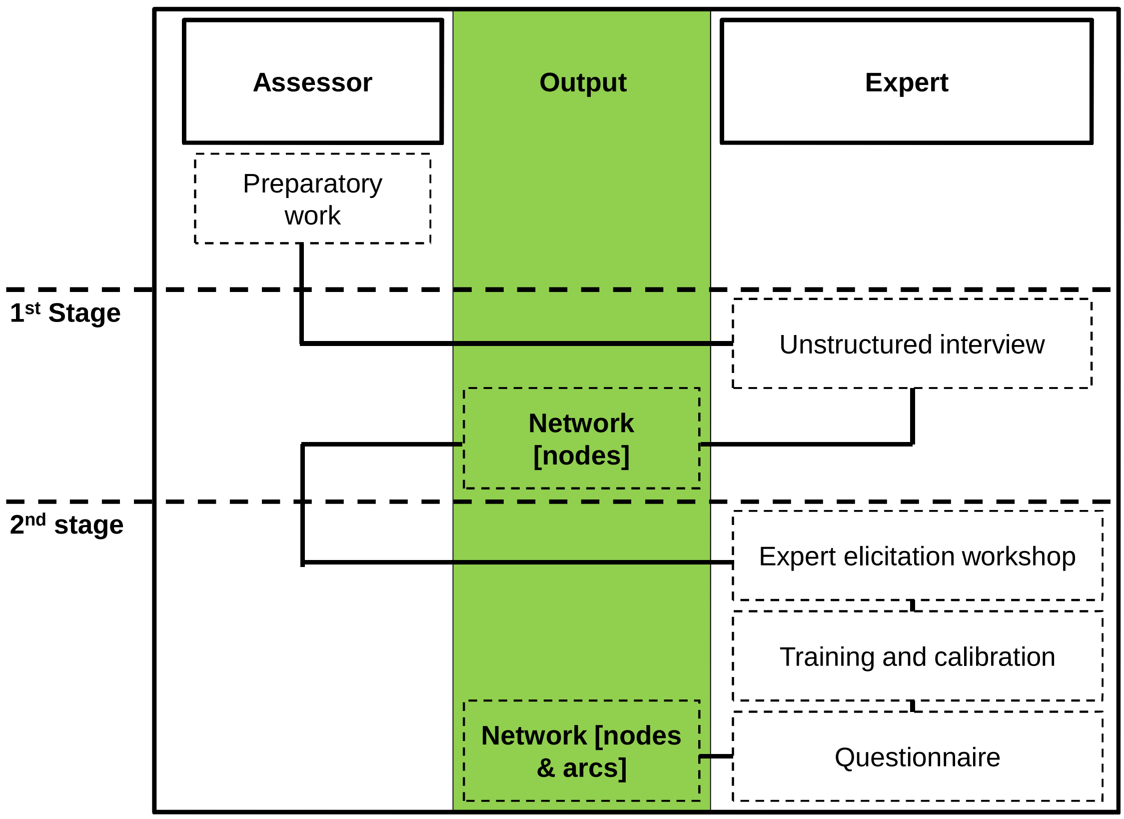

Figure 7.1 Diagram of the knowledge acquisition protocol

[Key] The knowledge acquisition protocol includes a preparation stage and two separate elicitation exercises

7.2.1 Stage one – a collection of network nodes

The first stage focuses on developing a list of components that define the system. From a network perspective, this involves defining them as nodes of the network. This selection adopts a structure that differs from classic scoping or screening techniques, where a large number of elements are proposed and subsequently excluded based on their value and significance to the models objective (Pollard et al., 2008a; DH, 2001). Instead, the model focuses on developing a comprehensive analysis, where all theoretical factors and pathways of exposure that may play a role in introducing the disease have to be included, regardless of significance. The adopted technique follows two principles:

System boundaries defines the system. Boundary variations are noticeable in the difference between closed and open systems. Closed systems have defined boundaries and are isolated from the influence of factors exterior to the system, for example a manufacturing process (Murthy and Krishnamurthy, 2009). Open systems on the other hand, have loose boundaries as these systems are influenced by exterior factors, making it harder to discern between what is to be included in the system and what is to be excluded. Open systems include most systems that develop organically such as organisations, ecosystems and most importantly, the system associated with IRA (Pearce and Merletti, 2006).

System size relates directly to the number of nodes considered in the network developed (Murthy and Krishnamurthy, 2009; Mitchell, 2006; Newman, 2003). The greater the number of nodes the greater the detail of the information produced. However, this comes at a cost regarding information needs, as the inclusion of extra nodes involves collecting extra information regarding the characterisation of that node's behaviour and of its relation with the network. Consider the following formula determining the number of variables to be elicited by the experts for the classic swine fever assessment, which considered two variables assessed per arc. The formula is $v = 2n\ (n\text{-}1)$, where n represents the number of nodes and v the number of variables that need assessing. A network including 15 nodes involves the elicitation of 420 variables. The inclusion of an extra node increases the number of variables to 480 that is 60 extra variables to elicit. The aggregation of components, based on behaviour and controls in place, presents the solution to control the size of the network. Components, that are considered to present a similar behaviour by experts and which are controlled by the same barriers were aggregated into a single node, thus maintaining the network at a manageable size while minimising the compromise to comprehensiveness.

The development of the network involved the elicitation of knowledge through a series of interviews. These were unstructured but focused interviews with high level officials, responsible for overseeing different areas of the system, including exotic animal disease specialists, border controls, animal health and food safety interviews (Cooke, 1994; Liou, 1992; Neale, 1988). Preparatory work involved collecting an extensive list of components that may play a role in enabling the incursion of an EAD and of the available controls preventing EAD outbreaks. Examples are available in the literature review (Section 1.3). The review was guided by a document published by Defra in 2010, “Exotic Animal Disease - Risk Pathways and Countermeasures: Report” (Defra, 2011a), and complemented by an extensive revision of the IRA, both expert and scenario based, and epidemiologic reports. The aim of the interviews was to define the nodes, based on the components and controls identified and complementing them where an expert felt it necessary. Due to the limited time available with the experts, to accelerate the development of a final version of the network, the information collected in the previous interview influenced the subsequent one and the network diagram was updated with each interview.

Expert selection focused on developing an informed oversight of the system. Expert requirements involved characterising the EAD sources, a general understanding of the system, its components and behaviour, and understanding of farming system associated with receptors. The expertise selected included:

- Individuals involved in the oversight of controls on international trade and movement of animal goods across borders.
- Individuals involved in the oversight of movements of animal and animal goods, veterinary controls and movements with the potential for transmission of the EAD within UK borders.
- Individuals with a deep understanding of the production systems associated with receptors to the EAD.

The TAG meeting members played a significant role in identifying individuals to invite as experts. Similarly, guidance was retrieved from list of experts used to develop Defra's Risk Pathways and Vulnerabilities Report (Defra, 2011a). Additional experts were added if interviewers suggested a specific expertise or individuals who could contribute to overcoming issues identified. This was the case for the first application to CSF where David Harris was included following previous interviews. In some cases, the experts selected for the interview suggested members from within their team to be integrated. For example, this was the case in two of the four interviews used to develop the CSF network, which were conducted with two experts simultaneously.

The output from this exercise was a compilation of network nodes alongside a summary definition for each (Annex 1 for CSF & Annex 5 for FMD). The nodes and respective definition form the basis of the work to develop during the second elicitation stage - the workshop. Following the interviewing stage the developed network was sent to the experts interviewed for comment. To ensure the validity of the final version, it was then tested and commented upon by the expert panel in a technical advisory meeting.

7.2.2 Stage two – assessing network connectivity

The second stage of elicitation involves assessing the network connectivity. The first step in achieving this is the identification of the seed variables (Cooke and Goossens, 2000). These can also be called performance variables, and will be the focus of the assessment. In this case, they are responsible for characterising the likelihood of disease transmission between two nodes and are based on two variables. These variables were defined with the assistance of experts during the interviews aimed at developing the network nodes and TAG meetings. The first variable describes the frequency of movements between two nodes. The second variable describes the efficiency of the control measures in detecting and eliminating the disease agent between those two nodes. The description of the variable is available in full in Section 6.3. The subsequent activity was the development of two independent ranking scales to assess the frequency of movements between nodes and the efficiency of the controls in place. Feedback from a technical advisory group alongside the data collected from the interviews provided the guidelines for the development of the scales. These are two independent frequency scales based on a logarithmic progression, which allows accounting for the high amplitude of values considered (Fleiss et al., 2003; Cobb, 1998).

The scales used for the CSF workshop are available in Figure 7.2. the complete form is available in Annex 3.

	World (non-EU)	EU (disease)	EU (free)	BIP	Environment & Wildlife	Labs	Pet shops, zoos	Gatherings	Retailers, restaurants	Feed factory	Human population	Vet, field workers	Slaughter	Livestock vehicles	Domestic, backyard	Waste disposal
Expert 1								*	*	*				*	*	
Expert 2				*				*				*	*	*	*	*
Expert 3		*			*				*	*		*	*	*	*	*
Expert 4	*	*	*	*	*		*				*					
Expert 5						*	*	*		*	*	*	*	*	*	*
Expert 6	*	*	*	*	*		*	*	*		*		*		*	*
Expert 7												*	*			*
Expert 8	*	*	*	*		*	*	*	*	*	*	*	*	*	*	*
Expert 9	*	*	*		*	*		*				*	*	*	*	*
Expert 10																*
Expert 11	*	*	*	*				*				*		*	*	*
Expert 12	*	*	*			*							*	*	*	
Expert 13								*			*	*	*	*	*	
Expert 14				*	*		*	*						*	*	
Expert 15																
Expert 16						*						*			*	
Expert 17								*	*	*			*	*	*	*
Expert 18																
Expert 19	*	*	*	*							*			*		*
Expert 20	*				*						*					
Expert 21								*					*	*		

Table 7.1 Results of the questionnaire put forward to experts, regarding their area of expertise.

The next step in the development of the second elicitation stage is the expert selection. Expert selection plays a key role in the development of a knowledge acquisition exercise (O'Hagan, 1998; Neale, 1988; Cooke and Goossens, 2000; Olson and Rueter, 1987). The second elicitation exercise – workshop – involved the development of a new list of expert needs. Here, the target was "practitioners' " expertise, that is experience in controlling or managing the work in specific nodes of the network (in the field). The process of selection involved:

- A list expressing expertise requirements for the exercise, by enumerating expert roles and agencies, was put forward to Defra partners. Based on the criteria a list of experts was developed by Defra partners and invitations sent (Annex 4).
- Following the definition of a final list of experts, a questionnaire was sent, via email, containing a short description of the task at hand and a simple question box to record their node preferences (simple tick the box). The invitational email is available in Annex 4.

The replies provided data on the experts' area of expertise. This ensured the availability of expert knowledge across all nodes considered in the network (Table 7.1). This information provided the basis for developing the composition of expert groups, which were the basis of the workshop (Annex 4). Expert availability played a significant factor in the experts selected for the workshop.

7.3 Classic Swine Fever Workshop - the elicitation protocol

The elicitation protocol was generated from a solution of compromises between the volume and quality of data, whilst considering expert availability. The 28 experts used for the CSF elicitation were available for a period of eight hours. During this period interactions with the experts included training and calibration as well as the elicitation of 544 variables. The agenda for the workshop (Table 7.2) describes the activities and material used during each exercise. A considerable part of the day activities was devoted to communication with experts using PowerPoint presentations. These aimed to inform on the task at hand, to help the experts interiorise the concepts of the elicitation and the aim of the project, and on how to use the ranking scales (PowerPoint presentations not included in the thesis for brevity).

Calibration exercises followed. The aim of these exercises (performed exclusively in the CSF workshop) was to accustom experts with the idea that any connection between nodes, regardless of how unlikely, must be included. These used prints-outs of the nodes and their definitions and A3 printouts of the interaction matrix (these are similar to that presented in Figure 8.2, however with the off-diagonal cells blank). Experts were asked to identify in the matrix all possible connection between nodes. The collective output of the exercises is displayed in the interaction matrix (Annex 3 – Figure 17.2). Experts filled the matrix almost in its entirety, which if very unlikely connections are to be considered was the expected result. The output resulting from these exercises was not inputted into the model.

Following expert training, experts focused on eliciting the seed variables. Due to the limited time available with the experts and the limitations in attendance, the technique selected involved direct elicitation of the variables using group consensus (3 to 4 experts) to ensure discussion between experts. To meet the workshop goals, experts were separated into two sets of eight groups, therefore the groups were A1, A2... A8, B1... B7, B8. Each expert was included in one group in set A and one group in set B (Annex 4). The workshop was set up so that multiple groups could work simultaneously and therefore multiple nodes were assessed during the same time slot (Table 7.2). This allows for quick progress in generating data but involves heavy preparation work, particularly regarding expert selection and allocation.

The exercise was preceded by a presentation, which reinforced notions on how to fill the elicitation form and the importance of filling all fields. Each group was instructed to assess a specific network node and the task proposed included assessing all outgoing connections from that node. Structure to the process was provided in the form of guiding questions to completing the exercise form, for each assessed connection. A projector displayed the guiding questions for the full duration of the exercise. These were the following:

1) Is the connection between node A to node X possible, where A is the node allocated to the expert and X any other node present in the network? YES or NO
2) If YES how frequent are movements between node A and X, using left side scale? (Figure 7.2)
3) If YES how efficient are the barriers preventing the movement of contaminated goods between them, using right side scale? (Figure 7.2)
4) Assuming the existing barriers are not 100% efficient, what is in your opinion the cause for barrier failure, using the comments section? (Figure 7.2)

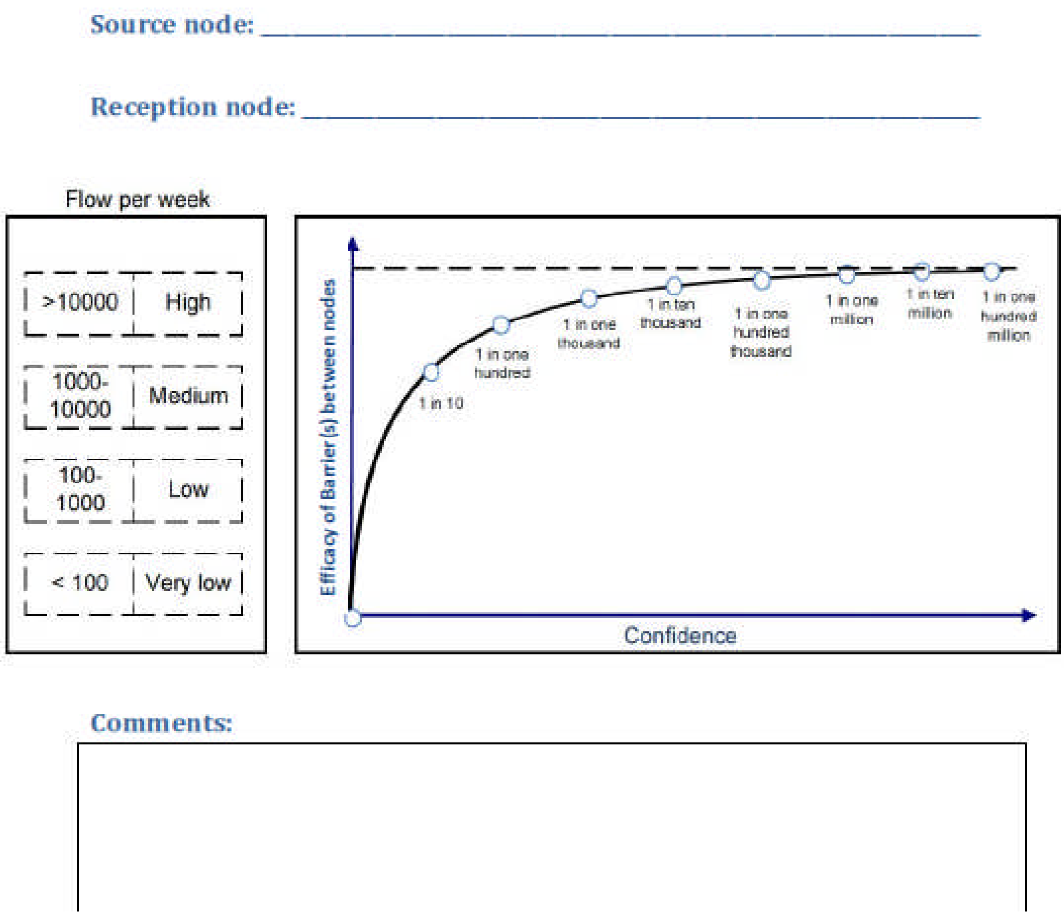

Figure 7.2 Elicitation form used in the CSF workshop to retrieve the seed variables from experts

The values for the variables were elicited through group discussion and expert consensus. The material used for the elicitation exercises included printouts of the node collection, documents with node definitions and unfilled printouts of the interaction matrix (Annex 1). Each group was provided with multiple elicitation forms, which provided the scales and comment sections necessary to characterise the outgoing connections detected between the node allocated and all other nodes considered within the network (with the exception of source nodes) (Annex 3). To aid experts in maintaining a discussion that was in line with the workshop objectives, mediators (João and Phil) moved from group to group to ensure the discussion and outputs produced were of the desired quality. Each group filled multiple forms. Once all groups completed the task, all possible connections within the network had been assessed and network connectivity complete, a network can be mapped. The output of the workshop is presented in the form of a FEP list in Annex 2.

Workshop Agenda					
Agenda	Task (performer)	Expert activity	Handout material	Objective	Resources needed - prior to event
10:00	Introductory presentation (Edgar and João)	Listen & question	None	[Introduction] Explaining the objectives and key concepts of the project. Assure concepts are understood and use of language / terminology consistent	Powerpoint presentation, Glossary of terms - poster [A0]
10:25	Edgar, João	Divide experts into 5 / 6 working groups	None	[Diversity of backgrounds] To ensure that groups are divers in background	Group allocations
10:30	Group work (Experts)	Using the network diagram and interaction matrices [presented] develop possible scenarios based on the available nodes	Network node diagrams in A2 sheet and IM (A3)provide to each group & Handout with the specification of what each node represents.	[Warm-up & engagement] Start discussion regarding possible import routes and division of those routs through the presented nodes.	A2 sheets; Node specification; A3 Interaction matrix with embedded nodes
11:15	Experts	Break	None	Rest / discussion	Tea & Coffee booked
11:30	Explain task (João)	Listen & question	None	To ensure that the task is understood	Powerpoint presentation [above]
11:45	Group work (Experts)	Group to sub-divide within each group - according to expertise by node	None	Ensure the group agree that the person assessing each node is the most appropriate	Use earlier powerpoint presentation
11:50	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Data Collection. Each expert will assess the likelihood of a connection between nodes. Assure that the task is equally divided be expert of each group. No expert should assess more than 15 connections.	Copies of A3 interation matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
12:45	Lunch	None - Lunch	None	Rest / discussion	Buffet lunch - pre booked
12:45	Preparation during lunch: João: Develop a simulation from one of the group's output; Facilitator: prepare copies	None - João preparing model in background	None	Introduce connections into the interaction matrix within the spread sheet; Run simulation; Present output to experts at the end of the work shop.	Prepare laptop programme - check with 'dummy run'; Organise copies of: Completed A3 interation matrices, copy of A3 network map completed by group
13:00	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Rearrange expert groups; provide different node to assess; and Repeat tast set for [13:15]	Copies of A3 interation matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
14:45	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Rearrange expert groups; provide different node to assess; and Repeat tast set for [13:15]	Copies of A3 interation matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
14:45	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Rearrange expert groups; provide different node to assess; and Repeat tast set for [13:15]	Copies of A3 interation matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
15:30	Output presentation (João)	Listen & question	none	Provide a sense of involvement to the experts	
15:35	Closure (Edgar)	Listen & question	None		

Table 7.2 Agenda for the CSF workshop

Workshop Agenda					
Agenda	Task (performer)	Expert activity	Handout material	Objective	Resources needed - prior to event
10:00	Introductory presentation (Edgar)	Listen & question	None	[Introduction] Explaining the objectives and key concepts of the project. Assure concepts are understood and use of language / terminology consistent	PowerPoint presentation, Glossary of terms - poster [A0], Node specification
10:15	João	Divide experts into 5 / 6 working groups	None	[Diversity of backgrounds] To ensure that groups are divers in background	Group allocations
10:30	Group work (Experts)	Using the network diagram and interaction matrices [presented] develop possible scenarios based on the available nodes	Network node diagrams in A2 sheet and IM (A3)provide to each group & Handout with the specification of what each node represents.	[Warm-up & engagement] Start discussion regarding possible import routes and division of those routs through the presented nodes.	A2 sheets; Node specification; A3 Interaction matrix with embedded nodes
11:00	Experts	Break	None	Rest / discussion	Tea & Coffee booked
11:15	Group work (Experts)	Group to sub-divide within each group - according to expertise by node	None	Ensure the group agree that the person assessing each node is the most appropriate	Name tags prepared during brake
11:15	Explain task (João)	Listen & question	None	To ensure that the task is understood	PowerPoint presentation [above]
11:35	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Data Collection. Each expert will assess the likelihood of a connection between nodes. Assure that the task is equally divided be expert of each group. No expert should assess more	Copies of A3 interaction matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
12:00	Break task	expert rank top five connection random node	Node list with number 1 to 5	Validation and concentration break	
12:05	Continuation	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Data Collection. Each expert will assess the likelihood of a connection between nodes. Assure that the task is equally divided be expert of each group. No expert should assess more than 15 connections.	Copies of A3 interaction matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
11:25	Break task	expert rank top five connection random node	Node list with number 1 to 5	Validation and concentration break	
12:30	Continuation	Revise the comments	Copy of the IM filed by the group the expert was	Certification that the comment section is files	Copies of A3 interaction matrices, copy of A3 network map
12:45	Lunch	None - Lunch	None	Rest / discussion	Buffet lunch - pre booked
12:45	Preparation during lunch: João: Develop a simulation from one of the group's output; Facilitator: prepare copies	None - João preparing model in background	None	Introduce connections into the interaction matrix within the spread sheet; Run simulation; Present output to experts at the end of the work shop.	Prepare laptop programme - check with 'dummy run';
13:30	Explain task (João)	Listen & question	None	To ensure that the task is understood	PowerPoint presentation [above]
13:40	Individual work	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Data Collection. Each expert will assess the likelihood of a connection between nodes. Assure that the task is equally divided be expert of each group. No expert should assess more than 15 connections.	Copies of A3 interaction matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
12:00	Break task	expert rank top five connection random node	Node list with number 1 to 5	Validation and concentration break	
13:40	Continuation	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Data Collection. Each expert will assess the likelihood of a connection between nodes. Assure that the task is equally divided be expert of each group. No expert should assess more	Copies of A3 interaction matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
12:00	Break task	expert rank top five connection random node	Node list with number 1 to 5	Validation and concentration break	
14:55	Continuation	Each expert will assess the likelihood of connection between nodes.	Copy of the IM filed by the group the expert was previously included in & limited Node Connection Forms.	Rearrange expert groups; provide different node to assess; and repeat task set for [11:50]	Copies of A3 interaction matrices, copy of A3 network map completed by group; A4 Node Evaluation Forms (Endless supply)
14:50	Experts	Break	None	Rest / discussion	Tea & Coffee booked
15:00	Avian Influenza	Listen & question	None		
15:15	Avian Influenza elicitation presentation (João)	Listen & question	None	To ensure that the task is understood	PowerPoint presentation [above]
15:30	tasks closure Closure/Output presentation (João)	Listen & question	none	Provide a sense of involvement to the experts	
15:35	Closure (Edgar)	Listen & question	None		

Table 7.3 Agenda for the FMD workshop the colour scheme

7.3.1 Foot-and-Mouth Disease elicitations

This project involved studying the introduction of two exotic animal diseases, specifically classical swine fever and foot-and-mouth disease. There were some differences in the model developed to study them, which forced modification to the elicitation protocol. The changes to the model, and subsequently to the elicitation process, followed a revision of the output produced for CSF by the members of the TAG. The revision highlighted the benefits of increasing the level of detail with which the nature of the movements between nodes was recorded and analysed. As a result, the modelling output changed by allowing the capacity to differentiate between legal and illegal movements and airborne transmission of the disease agent. The changes to the model are explained in detail in Chapter 9. These involved the multiplication of the seed variables by node, which increased from two to five. For brevity, this section focuses on the differences between processes and does not provide a complete description of the process of elicitation. The elicitation exercise, in its core remained unchanged.

7.3.1.1 The elicitation process

The process of expert selection (for both elicitation stages) and the elicitation procedure used in the first stage of elicitation were similar to those used for the CSF workshop. Here changes to the collection of nodes reflected the differences between the disease agent's transmission characteristics as well as to accommodate criticism from the TAG group following the first application to CSF. The process for selection and interaction with experts during the first stage of elicitation followed similar procedures to those described for CSF. Also, the exercise followed the same objectives and output format as that produced for CSF. The material presented to the experts to develop the exercises is described in Table 7.3. The workshop plan presented for the FMD workshop reflects the need to provide additional outputs (from two to five variables), whilst dealing with a smaller number of experts (Table 7.3). As a result, the following changes were made:

- Network nodes and respective definitions were revised to consider the transmission characteristic of FMD, and improved clarity in the separation between source, common and receptor nodes (Annex 5). This resulted in the expansion of the number of nodes considered in the network.
- Due to the increase in the number of nodes and the smaller number of experts available for the workshop, the calibration and training exercises were excluded from the agenda (Table 7.3).
- To manage a smaller pool of available experts, whilst requiring the assessment of a larger number of nodes, expert groups were composed of 2 to 3 experts (allocated to assess a node according to the stated node preferences) and each expert assessed 3 nodes. Each group was provided with printouts of the node collection and their definitions (Annex 5), and unfilled printouts of the interaction matrix.
- Groups were provided with forms to record five variables for each connection (Annex 6). These were incidence and barrier failure rate for legal and illegal movements and barrier failure rate for airborne transmission. To ensure a methodical analysis of all outgoing connections, a booklet, containing all possibly available outgoing connections from the allocated node to the remaining nodes in the network was presented to the experts. A connection

deemed impossible was characterised by the phrase not possible in the comment box. Each group was provided with a booklet tailored for their allocated node.

The output produced is similar to that developed for CSF, however discriminating between legal, illegal and airborne movement.

7.4 Data verification

Verification and validation of the data is an important step when performing an elicitation exercise (Cooke, 1994; Cooke and Goossens, 2000). However the limited time available to perform the elicitation alongside the extensive amount of data to elicit, meant that validation and verification exercises could not be included in the protocol developed for the workshop. Consequentially, data verification exercises took place post elicitation. The assessor verified the gathered data for inconsistencies or missing data values and comments. The experts responsible for assessing those nodes and arcs were contacted through telephone conference or if not possible via email, and asked to confirm or correct registered values.

7.5 Conclusions

Expert knowledge represents the sole source of information used data as input to run the model. Therefore, the development of the elicitation protocol plays a central role in ensuring the success of the study involving a trade-off between the large volume of data to be elicited and the quality of data produced. There is significant information regarding the necessary exercises to ensure a successful elicitation and the biasing effect in expert judgement by heuristics (Cooke, 1994; Liou, 1992; Cooke and Goossens, 2000; Slottje et al., 2008). However, it is lacking in their practical aspects, namely the development of exercises to retrieve information and experts' reaction to them. In light of these omissions, elicitation exercises become dependent on the assessor's experience.

The elicitation protocol presented is not entirely robust, presenting vulnerabilities regarding data verification opportunities and in the limited training of experts. However, given the information available in the literature, the limitations in the resources available and the assessor's experience in developing elicitation exercises, this is the best fitting protocol to ensure the objectives of the model were met.

8 A SYSTEMS APPROACH TO THE RISK ANALYSIS OF EXOTIC ANIMAL DISEASE II: ILLUSTRATION FOR CLASSICAL SWINE FEVER

This chapter presents the first application of the method described in Chapter 6, to study the UK's vulnerability to the introduction of Classic Swine Fever. Here, its application is described in detail and the results presented. Furthermore, the methods strengths and weaknesses are discussed, in comparison with risk analysis developed for CSF using conventional risk assessment methods.

> Submitted to Risk Analysis Journal:
> Delgado, J., Pollard, S.T.J., Snary, E., Black, E, Prpich, G., Longhurst, P., "A systems approach to the policy level risk assessment of exotic animal disease: network model and application to classical swine fever" (Submitted to Risk Analysis Journal on 24 January 2012).

8.1 <u>Introduction</u>

Globalisation and trade intensification have increased the vulnerability of developed countries to exotic animal disease (EAD) outbreaks (Otte et al., 2004); so much so that countries today are no more protected against EAD incursion than they were two decades ago (EFSA, 2006). Classical swine fever (CSF) is a notifiable animal disease caused by the CSF virus (CSFv) belonging to the genus *Pestivirus* of family Flaviviridae (Weesendorp et al., 2008; Moennig, 2000). Wild and domestic swine are natural hosts for the disease, and its manifestation varies according to the virulence of the strain, which may cause a range of mild to acute and sub-acute infections (Weesendorp et al., 2008; Moennig, 2000). CSF is an example of an EAD that challenges a country's defences continually. It remains present worldwide with positive detections in swine populations within Europe, Asia, Africa and the Americas from

2005 to 2010. CSF is endemic in parts of Europe having been detected in Bosnia and Herzegovina, Hungary and Slovakia in 2010 and in Germany in 2009, (Table 8.1).

CSF outbreaks		Year					
		2005	2006	2007	2008	2009	2010
Number of animals testing positive to CSF per year in European countries	Bosnia and Herzegovina	40	35	33			324
	Bulgaria	5	3	3	1	4	
	Croatia		13	112	4		
	Former Yug. Rep. of Macedonia		2	2	4		
	France	1		1			
	Germany	24	52	11		2	
	Hungary				164	27	382
	Montenegro (2007-2011)			16			
	Romania	1075	1438	159			
	Russia	8	2	7	1	4	
	Serbia (2007-2011)			18			
	Serbia and Montenegro (2005-2006)	489	401				
	Slovakia	4	5		3		24
European countries reporting at least one CSF outbreak/year (from 49 countries)		8	9	10	6	4	3
Countries outside Europe reporting at least one CSF outbreak/year (from 139 countries)		17	18	18	14	13	10

Table 8.1 Number of outbreaks and of infected animals worldwide from Jan, 2005 to Jan, 2011; with positive countries within Europe analysed in detail.

Though considered eradicated from the UK since 1966, CSF is highly contagious. Numerous routes of transmission exist (Table 8.2). The potential introduction of CSF via multiple transmission mechanisms places considerable pressure on the UK's capacity to prevent CSF outbreaks. The diversity and quantity of national and international animal movements, legal or otherwise, further enhances this increase. For example, the UK is exposed to the importation of legal and illegal meat consignments, the movement of people, e.g. tourists and migrant works, and live animal imports, amongst numerous other potential introduction routes (Defra, 2011a; De Vos et al., 2004; Hartnett et al., 2007). The detection of CSF in the UK puts in motion a contingency plan that focuses on containment and eradication of the disease agent.

Measures to prevent disease spread include trade restrictions and the elimination of potential disease sources through the elimination of livestock (Defra, 2010a). These measures contribute to the high costs of protection against CSF outbreaks (Morgan and Prakash, 2006; Saatkamp et al., 2000).

Understanding the risks posed through different transmission routes and the efficacy of protective barriers to control against introduction offers a means to improve preparedness against CSF outbreaks. A common approach for understanding the risks associated with CSF is the import risk assessment (IRA). Conventional IRAs, routinely used by governments (Defra, 2011c; Sabirovic and Hall, 2004), employ expert-based qualitative methods to provide an overview of the risks posed by each new outbreak and (or scenario-based quantitative assessments) to investigate specific pathways of introduction in detail (De Vos et al., 2004; Bronsvoort et al., 2008). Risk analysts suggest, as there are limitations to each approach, that a combination of methods may be necessary to secure a diagnostic understanding of the system responsible for preventing disease introductions. This in turn would provide valuable insights into the risk management options (Taylor, 2003; Peeler et al., 2006). Systemic models produce a more representative analysis of system behaviours, thus enabling risk analysts to better detect the interplay between improvements to individual components of the system and the improved protection afforded to the system as a whole. When used for CSF, these models can improve our understanding of the events that drive the overall likelihood of livestock exposures to the agent. This information then facilitates failure analysis (Murthy and Krishnamurthy, 2009; Dangerfield and Morris, 1992; Zio, 2009). Such assessments are not yet available in the literature, but proposed Chapter 6.

Transmission modes	Classic Swine Fever		
	Proven in Lab	Disease Import	References
Animal movements	+	+	(Moennig, 2000; Terpstra, 1987; Elbers et al., 1999; Artois et al., 2002; OIE, 2002; AHA, 2009; Stegeman et al., 1997)
Transport vehicles	+	+	(Weesendorp et al., 2008; Moennig, 2000; OIE, 2002; AHA, 2009; Stegeman et al., 1997)
Human contacts	+	+	(Terpstra, 1987; OIE, 2002; Stegeman et al., 1997; Ribbens et al., 2004)
Meat based food products	+	+	(OIE, 2002; OIE, 2002; Ribbens et al., 2004)
Wild boar	+	+	(Moennig, 2000; Artois et al., 2002; OIE, 2002; Fritzemeier et al., 2000)
Airborne	+	-	(Elbers et al., 1999; OIE, 2002; Stegeman et al., 1997)
Other carriers mechanical vectors)	+	-	(Liess, 1987)
Iatrogenic transmission	+	-	(Liess, 1987)
Artificial insemination	+	+	(De Smit et al., 1999; Elbers et al., 1999; Stegeman et al., 1997)
Vertical transmission	+	-	(Elbers et al., 1999; OIE, 2002)

Table 8.2 The transmission mechanisms for classic swine fever [CSF]

Routes of EAD introduction are the object of considerable speculation and, at times, the result of the systemic failure from the breakdown of multiple protection barriers, the combination of which might be considered unlikely. Examples of animal disease outbreaks suspected to have occurred through such pathways are the UK's CSF outbreak of 2000 in East Anglia (Gibbens et al., 2000) and the avian influenza outbreak of 2007, in Suffolk (Defra, 2007c). The root causes of both outbreaks remain uncertain and is attributed to an unspecified "very unlikely occurrence and isolated event" (Defra, 2007c). In light of the uncertainties associated with the pathways of CSF introduction, and of the roles played by different components of the system, we suggest a systemic analysis is necessary to provide improved insight at the policy level of potential disease introduction mechanisms. This work focuses on understanding the sequence of unlikely events that may result in a CSF outbreak, and the influence these events may have on compromising the protective barriers in place to protect against an outbreak. We apply a bottom-up network approach to further our understanding of EAD introductions, releases and exposure pathways. Knowledge about the vulnerabilities of a country's protection system can provide policy officials and decision makers with valuable insights about where to allocate resources that maximise protection, thus minimising the exposure to the CSFv.

8.2 Methods

A network model was used to assess the probability of UK swine herds being exposed to CSFv. Its design was structured to focus on the interaction between components of the system, represented as nodes, and the controls in place that reduce the likelihood of CSF exposure (Figure 8.1). To assess risks at the policy level, the model first requires a definition of the system. This includes several components, including the livestock and meat industries, facilities for trade, human population and pet shops as well as a mix of organisations and controls protecting the UK from outbreak (Defra, 2011a). Also important is an explicit description of CSFv transmission characteristics that play an important role in understanding system behaviour.

8.2.1 System definition

Transmission mechanisms for the introduction and spread of CSFv are summarised in Table 8.2. The first row describes the transmission modes demonstrated under laboratory condition; the second row describes the transmission modes detected in epidemiology reports from past outbreaks. The 'system' is defined here as the physical components that enable and prevent an incursion of the CSFv, the known transmission mechanisms and the regulations and tests used by the physical components to detect an incursion (Defra, 2011a). The structure of the system is recorded using a list of features, events and processes (FEP), which provides transparency and serves to record all assumptions made. The data recorded in the FEP list defines a network of features, represented as nodes and their adjacent connections, represented as arcs (Figure 8.1). Further information on network analysis (Borrett and Patten, 2003; Newman, 2003) and FEP list development (Freeze et al., 2005; Savage et al., 2004) is available. The manner in which a disease agent (CSFv) and the protective system interact is captured as a process and included in the FEP list. The term 'process' (P) describes the level of connectivity between two features, as well as the frequency of movement within a predetermined time interval. This defines an 'incidence'. The successful transmission of CSFv between two features depends on an event(s) that enables the agent to avoid detection and elimination. The nature of this event is recorded and a likelihood assigned to its potential for occurrence.

The features (nodes) and their adjacent connections (arcs) constitute the network (Figure 8.1). Estimations of the likelihood of exposure of livestock to CSFv, whilst considering the existing controls in place to prevent it, can be achieved using this system representation. An interaction matrix is one method for codifying a network model (Borrett and Patten, 2003) (Figure 8.2 for CSF in this study). Here, the diagonal cells represent the nodes of the network (black) and are described using the features from the FEP list. The off-diagonal cells are the arcs (white), and include the processes and associated events of the system. The rows contain all movements outgoing from the respective node. For example, row 8 represents all outgoing connection from the node domestic residence, node 08. The columns contain all incoming movements to the respective node. For example, column 14 contains all incoming movement to the node domestic and backyard animals, node 14. The movements considered possible, by the experts, are represented by the filled cells, containing the value for the reduction in likelihood of system failure associated with intervention in the respective process/event. The matrix provides for an image of the complete system, form sources to receptors, and allows a clearer visual of all available connections between nodes.

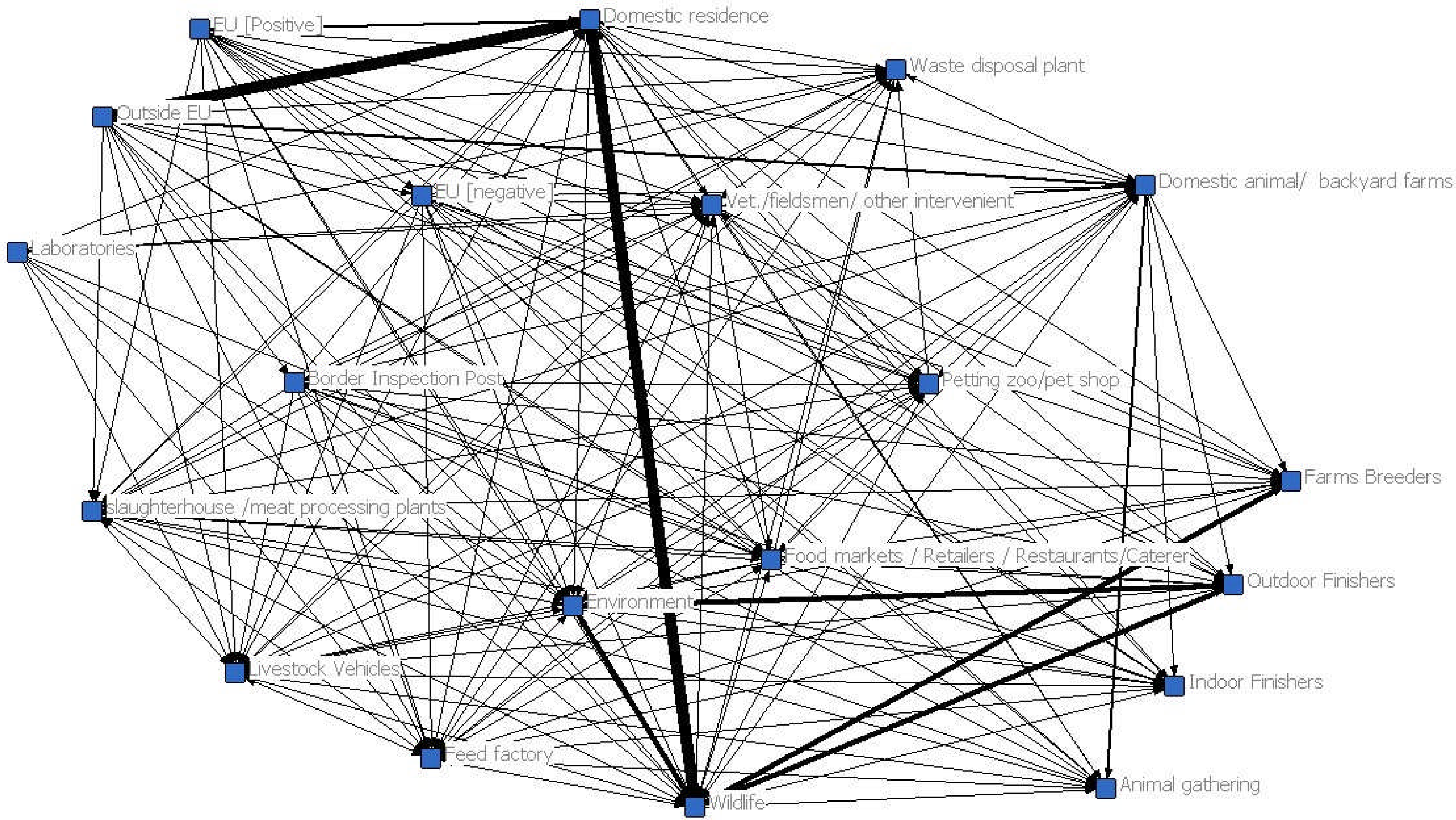

Figure 8.1 The network system developed for Classic Swine Fever (CSF)

[Key] Network based on the data recorded by the FEP list: the arc thickness is associated with the influence of that particular arc in system performance. The outputs of the sensitive analysis define arc influence.

01 Third Countries		2.39E-08	2.93E-10		3.65E-14	1.27E-06	4.16E-01	7.38E-13	5.56E-05	1.56E-08	2.51E-07	1.78E-15	4.22E-02	1.64E-05	4.12E-07	5.10E-07			
	02 EU [Positive]	3.36E-07			3.68E-12	1.27E-06	4.17E-02	7.40E-13	5.58E-06	1.56E-11	2.52E-09	1.92E-14	4.23E-07	1.65E-09	4.14E-08	0.00E+00	0.00E+00	0.00E+00	5.11E-06
		03 EU [Negative]			0.00E+00	6.38E-13	2.16E-08	3.65E-13	3.32E-07	7.71E-12	3.71E-09	4.88E-15	2.12E-11	2.55E-11	6.12E-11	2.55E-09	0.00E+00	0.00E+00	0.00E+00
			04 Border Inspection Post		6.00E-15	3.57E-12	8.50E-10	0.00E+00	1.92E-07	1.69E-13	2.16E-09	0.00E+00	1.69E-14	1.44E-08	3.53E-11	1.49E-09	1.49E-09	1.49E-09	1.49E-09
				05 Laboratories		1.26E-05	4.15E-05		5.55E-05	1.55E-09	2.51E-09	1.91E-14	4.22E-06	1.64E-07	4.12E-08				
					06 Slaughterhouse	3.80E-12	1.08E-13	0.00E+00	5.47E-12	3.31E-13	6.11E-14	0.00E+00	0.00E+00	4.13E-13	0.00E+00	4.21E-14	3.36E-14	3.38E-12	3.36E-14
						07 Livestock Vehicles	5.55E-07	0.00E+00	5.75E-04	4.83E-13		8.45E-12	3.01E-07	4.13E-11	1.04E-11	3.10E-05	3.09E-07	3.09E-05	3.09E-05
						4.52E-04	08 Domestic residence	2.59E-06	2.35E-03	5.48E-06		3.44E-14	1.50E-03	1.81E-04	4.35E-01	1.81E-02	1.29E-07	1.29E-05	1.29E-07
					2.08E-13	1.25E-07	0	09 Petting zoo/pet shop	6.53E-07	5.89E-09	7.34E-08	9.59E-12	4.13E-08	4.91E-07	1.21E-06				
			0.00E+00			3.56E-14	2.37E-05	4.57E-10	10 Vet./ fieldsmen	1.12E-11	9.70E-07	1.27E-09	1.89E-05	6.47E-08	1.52E-07	6.70E-03	6.59E-08	6.59E-04	6.59E-04
					5.87E-13	3.50E-06	0	0	1.84E-06	11 Waste disposal plant	0	2.71E-07	1.14E-11						
						4.36E-12	1.05E-11	1.90E-12	0	2.11E-09	12 Food markets/ Retailers	3.53E-11	3.03E-09	1.79E-07	4.37E-08		1.86E-05	1.84E-05	1.84E-05
					0.00E+00	1.42E-14		0.00E+00	2.89E-10	0.00E+00	3.11E-15	13 Feed factory	1.56E-11	2.11E-15	4.00E-15	2.26E-10	2.26E-07	2.26E-08	2.26E-08
			2.15E-07		3.09E-12	9.26E-05	3.03E-04	5.19E-12	4.83E-03	1.10E-07	5.42E-05	7.10E-11	14 Domestic backyard animals	3.70E-04	8.92E-04	3.83E-02	2.40E-09	2.40E-05	2.40E-09
						1.05E-04		0	1.84E-06	0	0	0.00E+00	1.01E-03	15 Environment	1.67E-13	1.43E-08	0	1.42E-01	1.42E-04
					6.06E-12	3.63E-12	2.02E-11	1.01E-09	1.90E-04	1.72E-09	2.13E-08	2.79E-13	1.18E-04	1.43E-01	16 Wildlife	1.46E-07	1.46E-01	1.46E-01	1.46E-04
																17 Animal gathering			
																	18 Farms Breeders		
																		19 Outdoor Finishers	
																			20 Indoor Finishers

Figure 8.2 CSF interaction matrix

[Key] Diagonal cells (black) network nodes, off diagonal cell (white) network arcs: The cell values and colour scheme presents the results of the local sensitivity analysis, the reduction in likelihood of system failure (Red cell represent a reduction in likelihood on system failure > 10 %; orange cells a reduction >1 %; and amber cells reduction > 0.1 %,) , where highlighted cells represent specific process/events where intervention will produce a greater impact in reducing system vulnerability.

8.2.2 Elicitation process

The literature is incomplete on the causes of failure for the multi barrier system required for detecting and eliminating CSFv. To overcome this, the model was informed by CSF transmission data elicited from experts (O'Hagan, 1998; Van der Fels-Klerx et al., 2002). Twenty-eight experts informed the exercise according to expertise, domain background, and availability with the aim of providing broad network coverage. The process of elicitation is described in further detail in Chapter 7. The workshop was 8 hours in duration and included training, as well as elicitation, with senior policy officials. This was the main information gathering exercise, where the relationships between the 20 features (nodes) in the network were assessed (Figure 8.1). This required extensive data input, and to reduce the workload for the experts, small groups were formed according to expertise (minimum 3 people), and allocated to relevant nodes. Each group was responsible for assessing all the outgoing connections to the remaining network nodes. For example, the assessment of node 07 (livestock vehicles) required assessments of all connections (arcs) adjacent to this node, hence from 07→01, 07→02, up to 07→20. For each cell, experts estimated the incidence and barrier efficacy (Chapter 7, Figure 7.2) and provided commentary on the causes of failure and the best and worst case assessment. Incidence is used to represent the number of times a connection is attempted per week, with or without successful transmission; i.e. the degree of 'challenge' to the system. Barrier failure represents the number of times a barrier fails to detect and/or eliminate a disease agent by reference to the number of times a connection is attempted. Two values were retrieved from the experts - a best and a worst case evaluation of barrier efficacy. The data also included a description of the events promoting barrier failure and a classification according to error type - human and/or system error. Data from the workshop was introduced into an interaction matrix coded into a pre-programmed Excel ™ spreadsheet. The model was used to generate all scenarios of CSFv introduction, accompanied by a sensitivity analysis to determine the *process/event(s)* that had the greatest influence on system performance. Follow up sessions, via email and telephone conferences, dealt with data verification issues; for example, missing values, comments and corrections. Results were finally validated by a sub-group of experts to ensure inputs and outputs were valid and within scope.

8.2.3 Generation of CSF introduction scenarios

Scenarios of CSF introduction are sequences of events that allow CSFv to be exposed to a UK pig herd. Scenarios were simulated using a pre-programmed Excel™ spreadsheet that described the network as an interaction matrix (IM, Figure 8.2), and a computer model that detects any possible sequence of events (to a maximum of successive 5 events) that allow exposure to occur. The likelihood of each scenario is estimated using the equations described in Section 6.3. The output of the scenario simulation is a list of all pathways that allow the disease agent to contact the receptor. That list includes a description of all nodes composing the pathways and a respective likelihood (P) estimate. The sum of the (P) values from all pathways represents the overall system performance value, or aggregate likelihood of exposing a pig herd to CSF.

8.2.4 Sensitivity analysis

To analyse the sensitivity of the model's output to changes in the input, the probability of transmission in the input parameters was changed using a sensitivity analysis (Frey and Patil, 2002; Hamby, 1995). The barrier failure rate associated with the process/events enabling transmission between nodes was nominally reduced by 50%

(i.e. barriers made less susceptible to failure), simulating an improvement to the controls of the disease. Two analyses were then performed: a) the effects caused by individual barrier improvement, using a 'one-at-a-time' sensitivity analysis; and b) the improvement of clusters of barriers associated with the nodes. For each increase in barrier integrity, a new system performance was estimated and compared to the base case above. Nodes or arcs presenting higher percentage values represent the greater influence on network behaviour. At these nodes, policy intervention is likely to have the greatest impact on reducing the vulnerability of the system to a future CSF outbreak.

8.3 Results

Scenarios comprising a sequence of process/events were used to describe how pig herds can be exposed to CSFv. These represent pathways of introduction. For this case study, a single set of core principles was adopted for scenario generation. First, a scenario was defined as starting in one of the three available source nodes, i.e. 01 - Third Countries; 02 - EU Positive; 04 – Laboratories (Figure 8.2). Next, the scenario was deemed to terminate when the disease agent reached one of four termination nodes, defined as the point where a single domestic livestock pig is infected. The terminal nodes are 17 - indoor finishers; 18 - outdoor finisher; 19 - farm breeder; 20 - animal gatherings. Finally, the scope of the scenario was managed by limiting the maximum length of each pathway (or number of nodes visited) to k = 5, where k denotes the length of pathway (Borrett and Patten, 2003). This value was chosen based on available computing capacity. Even with this assumption, the model produced some 56,269 theoretically plausible introduction scenarios (pathways) derived from the three sources. Each scenario represents a failure to detect and eliminate the disease agent prior to exposure to pig herds and thus represents failure of the multi-barrier system. A probability estimate is presented for each scenario, which ranged from 10^{-3} and below. The pathway scores and the overall system performance do not consider on going outbreaks in foreign countries or the quantity of imported goods at any given moment. Critically for readers, this does not represent a measure of the current residual risk of CSF exposure to pig herds (Murray, 2002; Bronsvoort et al., 2008). Rather used comparatively at the policy level, this analysis provides an opportunity to assess the influence of exposure scenarios and failure in the barrier between two adjacent nodes in the exposure to CSF thus enabling the identification of risk drivers.

The interaction matrix presents a systemic risk map of the network indicating the key network sensitivities. A colour scheme was used to classify the results of the sensitivity analysis at an arc level and to indicate the influence that process/events have on system behaviour (Figure 8.2). The columns represent all incoming connections (upstream) into a particular feature while the rows represent all outgoing connections (downstream). Upstream interventions represent preventative measures while downstream interventions represent containment measures. For example, Feature 01 represents a disease source where the only intervention measure is through containment. Similarly, for features representing receptors, 17, 18, 19 and 20, only preventative measures are available.

Figure 8.2, the interaction matrix, presents a powerful visual tool to identify key arcs that exert greater influence in the system. For example, closer review of node 08 - domestic residence (representing the human population) reveals the movements associated with the introduction form a of CSF form a third country (node 01) to a domestic residence and movements from the domestic residence to wildlife (node16), e.g. rubbish or scraps in FEP list, are most vulnerable (Red). Also, the matrix identifies wildlife as posing a threat to multiple livestock production units (nodes 18 and 19) and thus of exposing livestock to CSFv (Figure 8.2). Figure 8.2 displays the results for the worst-case sensitivity analysis. Here, the influence is separated according to three levels, presented in a colour scheme. The process/events presenting an influence higher than 10% are presented in red. For example, the two arcs P outside EU (node 01 to 08) and C wildlife (node 08 to 16) discussed above. In addition to these, process/events associated with wildlife and environment, from node 16 to 15 (14%), from node 16 to 18 (15%), from node 16 to 19 (15%) and from node 15 to 19 (14%), also present a significant reduction on risk of livestock exposure (red in Figure 8.2). The interaction matrix allows easy identification of the most influential nodes in the network.

The results of the node influence analysis are presented in Figure 8.3. This describes network behaviour, considering a best-case and worst-case scenario of barrier performance. For both best and worst case analysis, the source node outside EU had significant influence on network behaviour, creating a reduction in overall performance of 46% and 49% for worst and best case conditions, respectively. This suggests that intervention at source may be the best control option. Under best case conditions, animal gatherings (46%) and domestic animals (44%) also proved influential, while worst case conditions reveal domestic residences (46%), and wildlife (44 %) as most influential. Interestingly, the same nodes - animal gatherings, domestic animals, human population and wildlife - are influential under both best and worst case conditions.

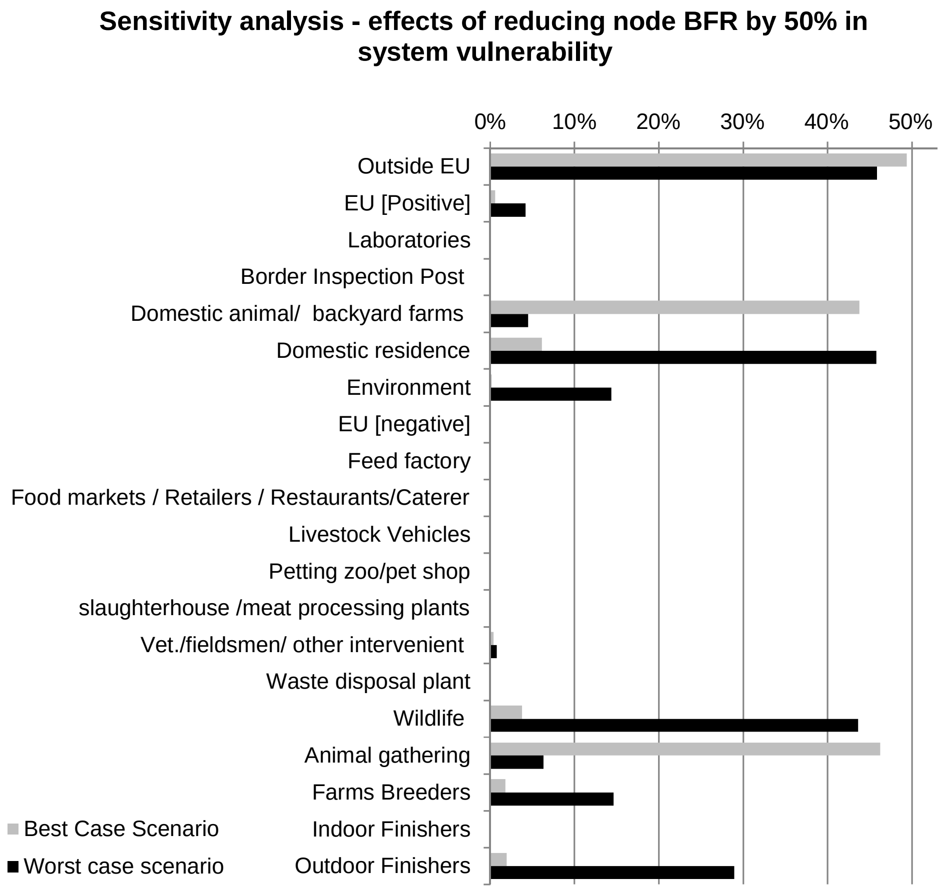

Figure 8.3 CSF node sensitivity analysis

[Key] the influence of each node is measure by calculating the reduction in percentage the performance value in comparison with the base case; the chart presents sensitivity analysis for both best and worst case scenarios

A more detailed analysis of node “05 domestic residence” is available in Figure 8.4. This focuses on a worst-case assessment of all process/events directly associated with domestic residences. The movement of goods between countries outside the European Union (outside EU positive) and the human population were shown to be highly influential to system performance (42%). Similarly, the link between the human population and wildlife (represented by the wild boar population) was also shown to be highly influential (44%). The arc representing the movement of goods from European countries had only modest influence (4%). The arcs (P) outside EU and (C) wildlife, represent the specific movements of goods and animals, where intervention results in a significant reduction in the vulnerability to future CSF outbreaks. The prefix (P) stands for preventative measures and represents incoming movement to the target node. In contrast, C represents containment measures, representing outgoing movements. The percentage values, for example 44% for C wildlife, means that an intervention that successfully increases containment reduces the risk of transmission by 50%, produces a reduction by 44% in the likelihood of a future CSF outbreak. Comparing the outputs presented, the interaction matrix allows a systemic perspective of the influence each process/event has in the overall system performance however the sequences of histograms (nodes and arcs) communicate the output without loss of information.

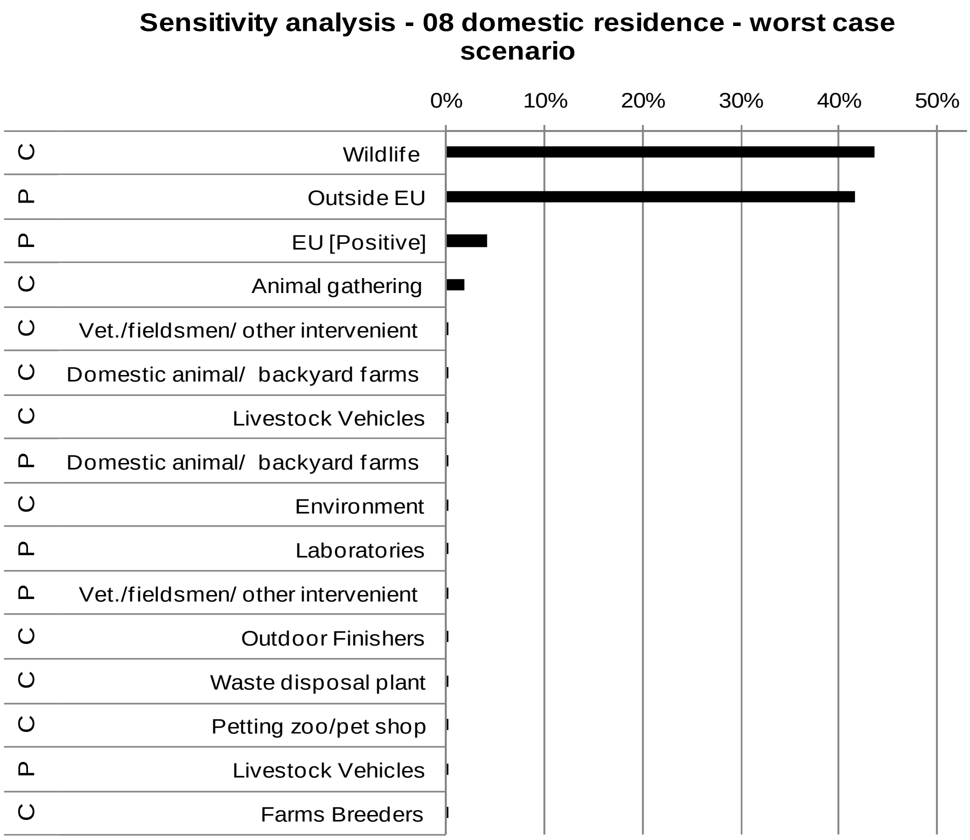

Figure 8.4 Sensitivity analysis of the node “08 Domestic residence”

[Key] Analysis of the arcs responsible for adjacent connection (upstream and downstream) to the 08 domestic residence nodes [P] preventative representing upstream nodes and [C] contingency representing downstream nodes

8.4 Discussion

Systemic network models allow for an examination of the interplay between the local and global aspects of a network at the policy level. The histograms provide stakeholders with a top down analysis of the system, which is consistent with the approach to developing a better understanding of system behaviour using the conventional approach to developing risk assessments (Taylor, 2003; Peeler et al., 2006). This approach captures both expert judgement and scenario development, common with traditional IRAs. Two independent sensitivity analyses were performed to assess vulnerability within the system. A first level analysis was performed at the node level, enabling identification of the features (i.e. nodes) exerting greatest influence on network behaviour. A second analysis was performed at a process/event (i.e. arc) level, which enabled understanding of those arcs influencing network behaviour as well as providing information about interventions. This analysis is useful for informing interventions that may influence network behaviour, while minimising investment.

8.4.1 Increasing resilience against a future CSF outbreaks

A study by EFSA suggests that in 2006, countries were no less susceptible to an EAD outbreak than they were 20 years ago (EFSA, 2006). The enormous progress in disease monitoring, surveillance and diagnostics has been offset by the increase in communication and contact via global trade. Furthermore, CSF is present worldwide with 13 countries declaring outbreaks in 2010; 2 of which were EU partners (OIE, 2010). The peril of introducing CSF into the UK remains. Worldwide eradication stands as the definitive objective when dealing with EADs. Our analysis supports this concept, with our sensitivity analysis revealing that disease containment in third countries produces the greatest increase in system performance and overall robustness. Nonetheless, eradication of CSF is unlikely to be achieved in the forthcoming decades, and detection and elimination of outbreaks remain the most viable defence options (EFSA, 2006). Surveillance is vital and the UK has in place a system for the early warning and elimination of threats. The system is complex, consisting of multiple controls, each which may be susceptible to failure. Occasional system failure is exemplified by outbreaks in 1971, 1986 and 2000; events' occurring after 1966, the year the disease was officially eradicated from the UK (Defra, 2006).

In assessing the robustness of the system, the analysis identifies a number of known threats as well as previously unidentified ones. This was achieved by assessing the level of influence each individual node has on system behaviour (Figure 8.3). Even when assigning different weightings to the nodes (assessment under worst and best case conditions), similar nodes were identified as highly influential, although with variation in the level of influence. This difference in level results from a different approach to assessing the efficiency of the barriers preventing transmission of CSF. The results from the worst-case assessment adopted a conservative mind-set whereby confidence in the controls, particularly if the general population was involved, is low and this identified threats such as domestic animals and animal gatherings. In contrast, the best-case conditions adopted an optimistic mind-set and identified areas where controls are limited and their effectiveness is unknown; for example wildlife and the environment as well as domestic residences.

Beyond the capacity to identify the nodes within the network with greater influence over its robustness, our model provides enough detail to study the effect of specific events that permit transmission between nodes, thus compromising system robustness.

The matrix (Figure 8.2) displays the upstream and downstream arcs connecting a node. This allows the analysis to detect node frailties as well as provide guidance as to where best risk management resource allocations are made. Concerning disease introduction from countries outside the European Union, experts were most concerned with connectivity to domestic residences and with backyard and domestic animals. They believed that *"risk targeted enforcement was unable to check all passengers and packages and there was a lack of awareness amongst travellers"*. With respect to the exposure of livestock, outdoor farms were deemed most vulnerable, particularly those with high contact with wild pig populations and the environment. Concerns with wildlife contact refer to the possibility of a *"wild boar entering the unit or of a young domestic pig escaping from premises into the environment and back [Evidence from Belgium]"*, in FEP list.

8.4.2 A new approach to assessing risk and develop strategies prevent EAD outbreaks

The objective of this work has been to develop a tool requiring minimal expenditure of resources whilst providing significant data for the development of guidelines and strategies for reducing the likelihood of livestock animals to EAD agents at the policy level. Previous studies have investigated the specific role of most components (i.e. nodes) in the network investigated here. For example most of the CSF dedicated qualitative IRAs identify the human population as a driver of exposure as well as backyard livestock, restaurants, caterers and food markets, wildlife, livestock lorries, and importation of live animals as risk factors (De Vos et al., 2004; Martinez-Lopez et al., 2008; Hartnett et al., 2007; Bronsvoort et al., 2008). However, conventional IRAs harbour methodological limitations that condition the quantity and quality of the insight produced. Conventional risk assessments, explicitly scenario-based assessments, rely on the research literature and on past epidemiological reports to define the pathways of exposure to be included in the assessment. Such literature is limited regarding the pathways of introduction and exposure of pig herds to CSF, or to any EAD, compromising the capacity to deliver a truly comprehensive analysis of the risk of exposure to CSF. Moreover, given that the cause of most EAD outbreaks remains inconclusive, a significant portion of introduction and exposure pathways will not have been previously assessed, which is a distinct limitation. This model provides an alternative approach, which through the application of a computer model alongside smart use of expert opinion allows for the generation of the pathways of exposure. This characteristic enables this model to consider pathways overlooked by previous assessments applied to CSF and thus overcomes the current limitation in the research literature. In addition, in scenario-based assessments, pathways of exposure are assessed in isolation and any mitigation strategy developed based on these assessments fails to provide an estimation of the systemic consequences of any intervention. Therefore, by treating all pathways equally, irrespective of likelihood, and considering how interventions affect the entire network our model considers less likely and previously unknown pathways, whilst providing an estimate of the impact a particular measure will have on overall system performance. By addressing the limitations of conventional IRA methods, we have developed a tool that provides a decision making body with insight regarding the system behaviour and targeted intervention activity leading to improved resilience against an EAD incursion.

In doing so, systemic models strike a middle ground between expert-based qualitative and scenario-based quantitative assessments. The network model develops a compromise between assessing the total system and the level of detail with which the pathways are analysed. The expert elicitation considers the multiple barriers to exposure available in the pathways. However, it does not allow discerning the influence these pose individually in reducing exposure. Therefore, the network model produces a lesser level of detail comparatively to scenario-based models, based on event tree representations of the pathways. Nonetheless, the model does provide an analysis of all theoretically possible pathways of exposure. Consequentially the network model develops an insight on the system, which has so far been out of scope from the assessments applied to study the introduction of CSF or to any EAD agent.

The large scope of the network associated with the scarcity of information on the causes for EAD introduction into the UK represent a gap in available information to use as an input to the model. Therefore, the model relies on expert opinion, where expert judgements provide the values to incidence, barrier failure rate and a description of the causes of failure to detect and eliminate CSFv. Expert opinion, as a source of information exposes the model to the inaccuracies associated with the elicitation of expert judgments (Cooke, 1994; Tversky and Kahneman, 1974). Expert biases have a negative influence in the accuracy of the output produced (Cooke and Goossens, 2000). Nonetheless, in light of the scarcity of data associated with the events enabling the introduction of CSFv into the UK, expert opinion stands as the sole source of information available to perform such an assessment. Furthermore, the expert opinion represents the most up to date source of information. Therefore, despite inaccuracies resulting from the capacity to retrieve information from experts, the results produced by the systemic model represent the most current assessment of the control measures applied to prevent the introduction of CSF into the UK.

8.4.3 Validation of the model

The exploratory nature of this assessment, as of most IRAs, signifies that its validation cannot be undertaken by comparing outputs with known values. The results produced, as well as the variables elicited, are theoretical and should not be used to reflect actual system state in space and time. The analysis is used in an exploratory mode and at the generic, policy level to inform decisions on policy and regulatory options for intervention. Therefore, it is necessary for the model to be validated by peer review assuring all assumptions are reasonable and the mathematical computations reflective of the system (OIE, 2011c; Murray, 2002; Ahl, 1996). The validation adopted here comprised of development stages where the model was structured using currently available documents and information. At the end of each stage, the latest developments were presented to a technical advisory group (TAG) composed of experts from different modelling and animal disease backgrounds. The objective of these meetings was to critique the model and suggest alternative solutions where appropriate. All aspects of the model were discussed, including mathematical modelling, assumptions regarding disease transmission and feature behaviour, the elicitation process, the data collected and the presentation of results. This study represents the first application of the method, therefore, following the elicitation process and alongside a TAG meeting a number of improvements for future application were highlighted, namely:

1. The network considers both legal and illegal movements of potentially threatening materials within the same process. The FEP list identifies and describes the nature of the movement. However, for processes where illegal and

legal movements are present, the model does not estimate each individual influence in system robustness.

2. For extraordinary situations where control barriers are not in place and common sense actions alone prevent events, such as the relation between livestock vehicles and domestic residences, future applications of the model should capture the effects of both phenomena.
3. The network considers England alone. Experts suggested a more useful application could consider the GB (England, Wales, Scotland and Northern Ireland).
4. Extent of the data to be elicited from experts alongside time and resource limitations associated with the workshop resulted in selecting best-case and worst-case approach, as opposed to a more comprehensive format (probability density functions) (Murray, 2002). Nonetheless, it provides estimates of the level of uncertainty associated with the barrier failure rates elicited (O'Hagan and Oakley, 2004).
5. Adoption of a stochastic approach to modelling the network, which incorporates the level of uncertainty into the outputs produced.

8.5 Conclusions

This is the first illustration of a network model within an import risk assessment context for EAD at the policy level. The model provides a level of insight not within reach of established IRA methodologies by providing a systemic perspective, whilst accounting for the particular events at the root of a potential CSF outbreak. This is a novel method, that has the potential to contribute to the robustness of England's defence against a

CSFv incursion, so generating insight on where to allocate resources, maximising the reinforcement of those defences..

8.6 Acknowledgements

We thank David Mouat, Bill Parish, Allick Simmons (Defra). JD was supported by Cranfield University and the Risk Centre. This research was part-funded by Defra, the AHVLA and a cross Council EPSRC, NERC, ESRC research grant (EP/G022682/1) awarded to the Risk Centre at Cranfield University.

9 A SYSTEMS APPROACH TO THE RISK ANALYSIS OF FOOT AND MOUTH DISEASE III: ILLUSTRATION FOR FOOT AND MOUTH DISEASE

This chapter presents the revision and application of the method described in Chapter 6. Here the model is applied to study the UK's vulnerability to the introduction of Foot and Mouth Disease. The model increased the level of detail with which the results are presented (discrimination between legal, illegal and airborne transmission).

9.1 <u>Introduction</u>

Foot and mouth disease (FMD) is an exotic animal disease (EAD) that is classified as notifiable by the World Organisation for Animal Health (OIE, 2011a). The disease is caused by the FMD virus (FMDv), a member of the *Aphthovirus* genus and *Picornaviridae* family (Alexandersen et al., 2003; Grubman and Baxt, 2004; Alexandersen et al., 2002) with manifestations ranging from acute to mild and sub-acute forms. Morbidity and mortality will vary according to the species infected and the virulence of the strain. Infections spread quickly within herds and are characterised by multiple transmission mechanisms.

Developed countries remain as vulnerable today to the threat of FMD as they did two decades ago (EFSA, 2006). Outbreaks resulting from this threat can result in severe economic losses resulting from disease eradication activities, lost market share and decline in tourism (Otte et al., 2004; Morgan and Prakash, 2006). The UK sustains a multi-barrier system that aims to prevent the introduction of EADs such as FMD. The control system is composed of a partnership of multiple agencies and independent agents, for example, Defra, Local Authorities, HM Revenues and customs, wildlife conservation groups and vets (Defra, 2011a). Its design uses redundancy to ensure protection against the multitude of possible EAD transmission routes. However outbreaks do occur, such as the outbreaks of 2001 and 2007, which exposed vulnerabilities in the multi-barrier system (Defra, 2008b; Scudamore, 2002; Anderson, 2008). Since these events, considerable investments to improve technological measures, e.g. diagnostic testing, were developed. Given these advances and the UK's geographic isolation, the likelihood of incurring as FMD outbreak via the import of live animals, returning livestock vehicles and/or wildlife has been reduced (Defra, 2011a). However, low probability incidents can still lead to animal disease outbreaks, especially those that occur in concert with other risk factors thus enabling disease agents to by-pass or overcome preventive controls (Reason, 1997; Pidgeon and O'Leary, 2000).

Government is responsible for developing and enforcing regulations that aim to reduce UK's vulnerability to FMD alongside other EADs (Defra, 2011a). Further improvement to the existing controls requires the prioritise of the potential failures of those controls that drive exposure to livestock. Critically, the priorities identified must reflect those of the entire system. Achieving this insight involves developing a comprehensive analysis of the interactions between FMD and failures within this multiple-barrier system. Such analysis is defined as a systemic analysis. Here we present a systemic risk analysis for the introduction of FMD into the UK. The objectives of this exercise were to identify vulnerabilities within the multi-barrier control system and the critical control points (CCP). CCP identify failures of controls where intervention is likely to produce the greatest improvement to UK's resilience to future FMD outbreaks (Delgado et al, 2010). The expectance is that this approach to develop priorities can better inform decisions about resource allocation for risk management solutions (Delgado et al., 2010). In addition, the results of this analysis inform the role that systemic bottom-up approaches can play within the current context of import risk assessment. Insights from this approach were compared with conventional RA methods and the implications of a systemic analysis on the development of risk mitigation strategies are discussed.

9.2 Method

The study provides a systemic risk assessment describing the vulnerabilities within in the UK's FMD protection system. It is based on the application of a network model developed to study the sequences of events that enable undetected introductions of the virus to pass into the UK and result in an outbreak. The model analyses the various controls used to protect susceptible receptors from disease sources and assesses the influence that individual barrier failures have on the system's behaviour. The model uses a network of connections to simulate the British livestock system.

The first step to develop a systemic analysis is to define the system's boundaries. The system comprises several components of the livestock and meat industries, facilities for trade, human population and pet-shops, as well as a range of control processes (Defra, 2011a). FMDv transmission characteristics also play a significant role in system behaviour and are also accounted for.

9.2.1 Description of the system

The transmission mechanisms influencing the introduction and spread of FMD were retrieved from profiles of the FMD virus developed by governmental agencies (e.g. Defra) and the World Organ for Animal Health (OIE) to ensure agreement between the assumptions made during the preparatory work and the elicitation workshop. The profile of the FMD virus and its transmission characteristic are available in (OIE, 2011b).

System boundaries are defined by the (i) entities enabling progression of the FMDv, (ii) the FMD biological characteristics and transmission mechanisms and (iii) the control and protocols these entities and stakeholders have to uphold to ensure timely detection of the disease agent (Defra, 2011a). The system is recorded using a features, events and processes (FEP) list. Literature on the application of the FEP list to control exotic animal diseases (EAD) can be found in Section 6.1.4. The FEP list provides a transparent record of the elicitation process as it records key assumptions made by experts. Based on these data a network, representative of the system is generated. Literature on networks and FEP lists is available at (Borrett and Patten, 2003; Newman, 2003) and (Freeze et al., 2005; Savage et al., 2004), respectively.

The interactions between a disease agent and multi-barrier system are responsible for creating the conditions of a disease incursion. The starting point for system development drew upon previous work on classical swine fever (Chapter 8), to which changes were made to accommodate FMD and the differing outputs. The list of changes introduced to the network is as follows:

- The list of receptor nodes was expanded to include multiple farm types such as, pig farms indoors, outdoor and breeding units), dairy, beef and breeding cattle farms, outdoor and breeding sheep farms and mixed species farms;
- The node animal gatherings was removed from the receptors nodes and included as a node to assess their importance in disease introduction;
- The node domestic residences was redefined to represent the human population;

- The model was modified to account for the differences between legal and illegal movements and airborne transmission of the disease (arcs).

A FEP list records the nature of the interactions within the system. Network nodes were recorded as features and the arcs, representing the incidents driving exposure, were recorded as processes and events and process. Here, the processes represent the movements enabling transmission of the disease and the events represent the causes of failure to detect the disease during that movement. Values recorded in the FEP list are: (i) incidence value represents the frequency of the process and (ii) barrier failure rate associated with the likelihood of the event causing barrier failure.

9.2.2 The interaction matrix

The foundation to the study is the development of a systemic network (Figure 9.1). The network can be described using an interaction matrix (Figure 9.2), which enables an understanding of how sequences of events create pathways of exposure, connecting disease sources to susceptible receptors (Borrett and Patten, 2003). Within the interaction matrix the diagonal cells (black) correspond to nodes and the off-diagonal cells (white and colour) correspond to arcs. Features from the FEP list populate the node cells and the associated events populate the off-diagonal cells. The rows contain all movements outgoing from the respective node. For example, row 10 represents all outgoing connections enabling transmission from the node “2.7 Domestic animals/backyard farms” (Figure 9.2). The columns contain all incoming movements to the respective node. Each node is associated with 3 columns, where the column marked with an L represents legal movements, the column marked with an A represents airborne transmission of FMD and the column marked with an I represents illegal movements (top of Figure 9.2). For example, columns 19, 20 and 21 contain all legal, airborne and illegal incoming movements enabling transmission to node “2.7 Domestic animals/backyard farms”, respectively. The movements considered possible, by the experts, are represented by the filled cells, containing the value for the reduction in likelihood of system failure associated with intervention in the respective process/event.

The definition of illegal movements was the subject of great debate during the preparatory stages of the model. Following expert consultation illegal movements were broadly defined as “(non-compliant movements, sabotage, negligence, recklessness)” and experts were given leeway to interpret the concept of legal and illegal within the context of each individual process.

9.2.3 Elicitation process

Data to populate the model was provided by experts via two elicitation processes (O'Hagan, 1998; Van der Fels-Klerx et al., 2002). The first stage defined system boundaries and network nodes and was compiled through a series of interviews. The second elicitation process involved a one day workshop that involved 24 experts. The criteria and process for expert selection as well as the process of elicitation are described in further detail in Chapter 7. The workshop elicited information on the connections between the 26 network nodes (Figure 9.1). Values of likelihood were obtained through group discussions and consensus, with experts divided into groups of two or three according to their expertise. The group exercise involved assessing all outgoing connections originating from a particular node. These consider legal and illegal movements and airborne transmission independently (Figure 9.2). Each of these movements was characterised by its incidence and barrier failure rates and by the provided comments on the possible causes of barrier failures. Therefore, the elicitation produced a quantitative character of the network. Verification of the elicited data was carried out through follow-up interviews that addressed issues of data quality, missing values, comments and corrections (Cooke and Goossens, 2000). Care was taken to maintain the influence of biasing effects to a minimum and to assure the information gathered complied with data needs (O'Hagan, 1998; Meyer and Booker, 2001; O'Hagan and Oakley, 2004; Garthwaite et al., 2005).

9.2.4 Modelling scenarios of FMD introduction

Scenarios were simulated using a pre-programmed Excel™ spreadsheet that described the network as an interaction matrix (IM, Figure 9.2), and a computer model that detects any possible sequence of events (to a maximum of successive 4 events) that allow exposure to occur. The likelihood of each scenario is estimated using the equations described in Section 6.3. The output of the scenario simulation is a list of all pathways that allow the disease agent to contact the receptor. That list includes a description of all nodes composing the pathways and a respective likelihood (P) estimate. The sum of the (P) values from all pathways represents the overall system performance value, or aggregate likelihood of exposing a livestock to FMD. Sensitivity analyses were used to identify the *features* and *process/ events* that exert the greatest influence on network behaviour.

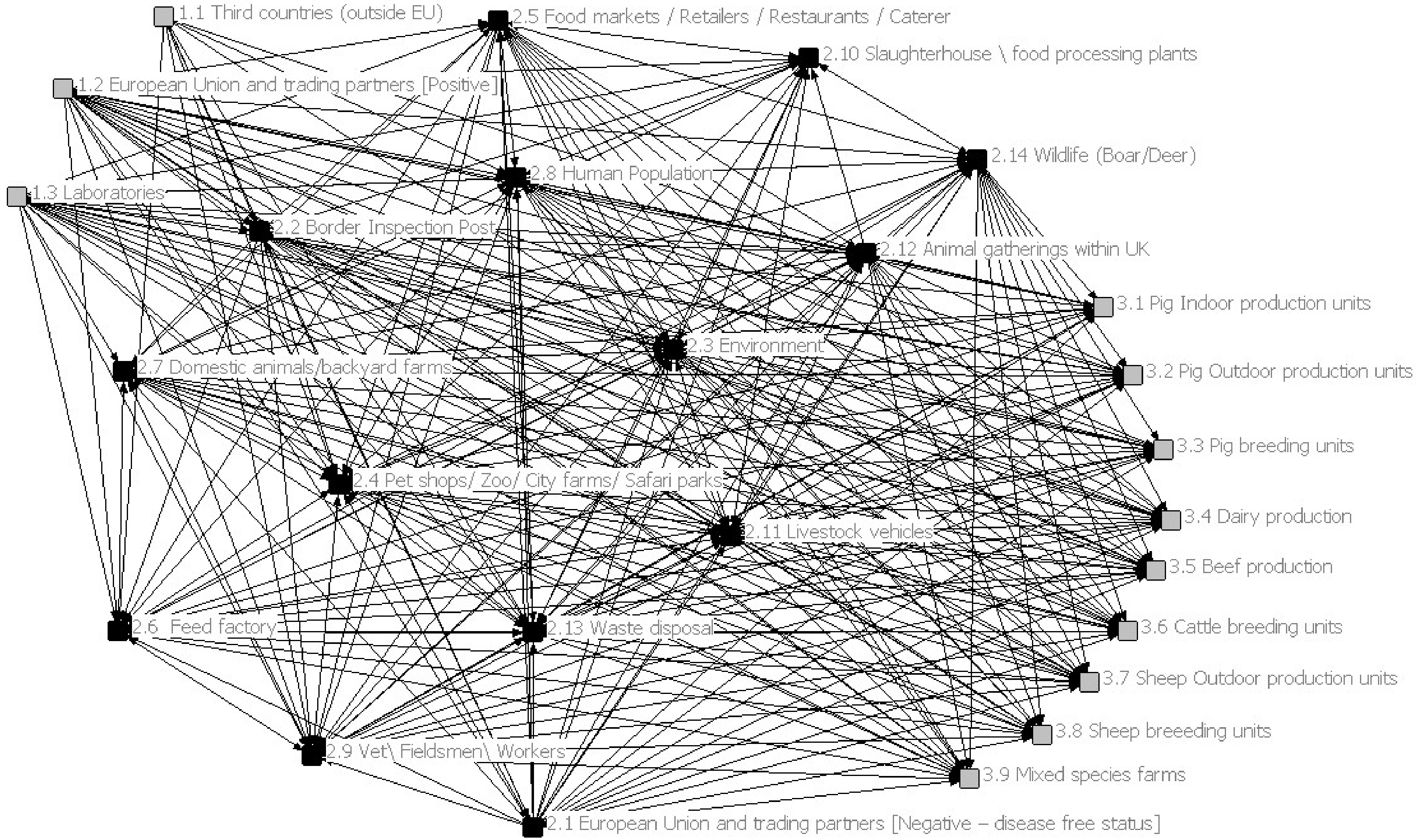

Figure 9.1 The network system developed for Foot and Mouth disease (FMD)

[Key] Nodes starting with 1 represent disease sources (Grey), nodes starting with 2 represent full functioning nodes (black) and nodes names starting with 3 represent terminal nodes (Grey)

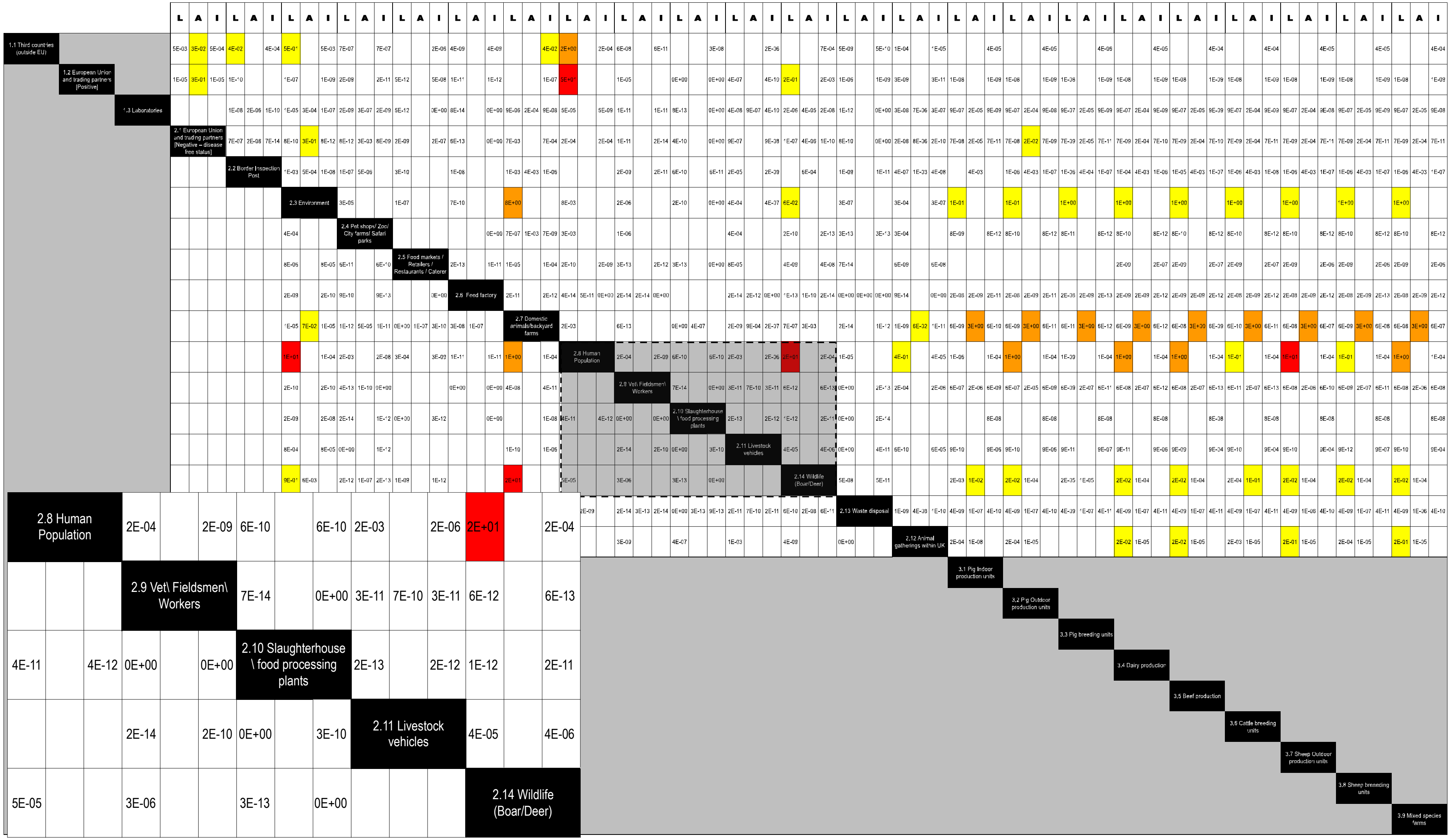

Figure 9.2 FMD Interaction matrix

[Key] Diagonal Cells (black) represent the nodes (features) and the off-diagonal cells represent the arcs (process events, where L – Legal movement; A – Airborne transmission and I – Illegal movements). Colour code identifies arcs where an increase in barrier efficiency (50%l) reduces the likelihood of system failure by >10% (red); > 1% (amber); > 0.01% (yellow).) b) represents a close up of a section of the matrix.

9.2.5 Results of the scenario generation analysis

A scenario is a combination of *process/events* that form a pathway, which describes the contact of FMDv with susceptible receptors. The process of formulating scenarios follows a set of core principles: (i) multiple sources of introduction exist. These are, "1.1Third countries" representing all countries where the disease is present, detected and undetected; "1.2 EU Positive" countries within the EU with ongoing confirmed FMD outbreaks; and "*1*.3 Laboratories" representing potential release of FMDv from a laboratory from within the UK Figure 9.5); (ii) simulation terminates when the FMDv reaches a group of predefined terminal nodes such as, "3.1 Pig indoor production units"; "3.2 Pig outdoor production units"; "3.3 Pig breeding units"; "3.4 Dairy production"; "3.5 Beef production"; "3.6 Cattle breeding units"; "3.7 Sheep Outdoor production units"; "3.8 Sheep breeding units" and "3.9 Mixed species farms"; (iii) scenario analysis develops pathways of length k = 4 (Borrett and Patten, 2003). This length was based on computational capacity and time limitations and resulted in 544,067 possible scenarios.

9.2.6 Sensitivity analysis

Based on the likelihood of each individual scenario a baseline for system performance was determined. This value defines the system vulnerability relative to an FMDv incursion (Frey and Patil, 2002; Hamby, 1995) and is used to determine the influence an intervention at a specific node or arc has on system performance. The adopted protocol involves the reduction of a barrier failure rate by 50%, followed by calculation of its effects on the overall system performance. By selecting different arc combinations multiple sensitivity analyses were produced. Two analyses were performed. The first, an *arc sensitivity analysis* was based on a one-at-a-time sensitivity analysis and detected the influence individual arcs (*process/events*) have on system behaviour. The results are presented in a colour coded interaction matrix (Figure 9.2), here used as a communication tool. The colour code identifies arcs where an increase in barrier efficiency of 50% reduces the likelihood of system failure by >10% (red); > 1% (amber); > 0.01% (yellow). The second sensitivity analysis was a *node sensitivity analysis* that was based on a global sensitivity analysis and considered all arcs representing outgoing movements from a node (Figure 9.3).

9.3 <u>Results and discussion</u>

The results are based on the outputs produced by the sensitivity analysis, which was used to define the drivers of system behaviour. In addition, this approach provided multiple perspectives of the system and its risks.

9.3.1 Systemic perspective of system risk

This perspective focused on displaying a complete image of the system under assessment. The representation of the system using an IM provides a systemic perspective in which all possible interactions are represented with the riskiest interactions - within the context of the full network – highlighted (Figure 9.2). Here the IM describes the results from the *arc sensitivity analysis.* From the analysis, the human population plays an important role for introducing the disease agent from foreign countries within and outside the EU. Driven largely by free trade agreements and free movement of people within the EU, this interaction is particularly difficult to control. The human population also plays a significant role in exposing livestock animals to FMDv. The systemic perspective rules out illegal movements as a significant source of risk as no illegal movements scored over the 1% threshold.

9.3.2 Defining priorities through a system of varying perspective from scoping to detail

This model generates systemic knowledge about the multi-barrier system protecting the UK against disease incursions and provides insight necessary to inform risk mitigation strategies and countermeasures. To do so priorities must be defined and key areas of intervention identified. These provide the basis for which interventions will produce the most effective results, akin to the critical control points. (Delgado et al., 2010). System size often complicates this task, the network and interaction matrix representations provide useful systemic understanding, however these compress knowledge into a single image resulting in information loss. This results from the large volume of information included in the picture as each node considers on average 65.3 connections to adjacent nodes separately including incoming and outgoing movements, legal and illegal activities and airborne transmission. Compared to the detail provided by numerical outputs, the communicative power of the interaction matrix is reduced by the broad categorical intervals used by the colour scheme.

A comprehensive output was developed using a sequence of analyses progressing towards increasing detail (Section 8.3). The output format results from the planned sensitivity analyses, which focus on nodes and *process/events* separately, assessing the network at different levels of detail. This enables a progressive narrowing of perspective thus permitting an increase in detail.

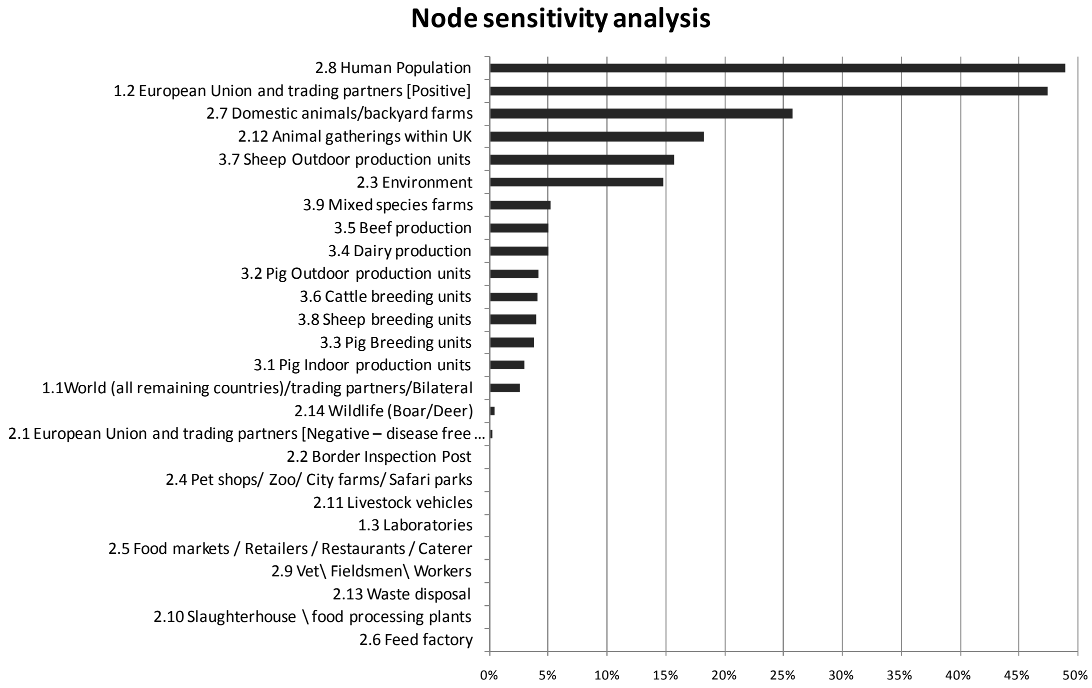

Figure 9.3 FMD node sensitivity analysis

[Key] Representing the nodes of the network in order of importance regarding their influence in the likelihood of system failure

The first stage of communication is associated with the *node sensitivity analysis*, which focuses on the identification of the network nodes possessing the greatest influence on the likelihood of system failure. Figure 9.3 displays the results of the 26 simulations with the influence of each node on system behaviour represented by the reduction in percentage to the base case of network behaviour. Human population (48,9%) and European countries [positive] (47.4%) had the greatest influence with over 40% reduction to the base case. This means that an intervention in all *process/events* (arcs) associated with these nodes may potentially result in a reduction of likelihood of an FMD outbreak greater than or equal to 40%. In contrast, other nodes such as waste disposal (2E-7%), slaughterhouses (8E-7%) and feed factories (2E-9%) have little influence on network behaviour.

The second stage of communication is associated with the arc sensitivity analysis. This communication focuses on the identification of process/events, i.e. movements, between nodes possessing the greatest influence on the likelihood of system failure, considering legal and illegal activities and airborne transmission of the disease agent. In contrast with the systemic representation, which is based on the same arc sensitivity analysis, this representation focuses on reducing information loss. The output presents the riskiest movements, associated with a particular node including both outgoing and incoming movements. Figure 9.4 displays the influence of each of the process/event associated with the node "Human population", presenting a selection of the ten highest influential process/events. A colour scheme differentiates between legal, illegal and airborne transmission – though is unnecessary for this node as all represented movements are legal. The arcs were described by the names of the nodes connected to"2.8 Human population" and the prefix [C] or [P] specified whether it was an outgoing or incoming connection respectively. Focussing on the two highest ranked, "[P] 1.2 European Union and trading partners [Positive]" (46.9%) represents the transmission of FMDv from a country within the EU where FMD has been confirmed and the British general population through, for example "*personal imports of meat based food products*" (comment for expert). The second highest arc "[C] 2.12 Animal gatherings within UK" (17.9%) represents the transmission of FMDv by the human population to an animal gathering, that is local markets trading live animals and animal shows. [P] and [C] provide an indication of the measures to be applied for each situation with [P] standing for preventative measures and [C] for containment.

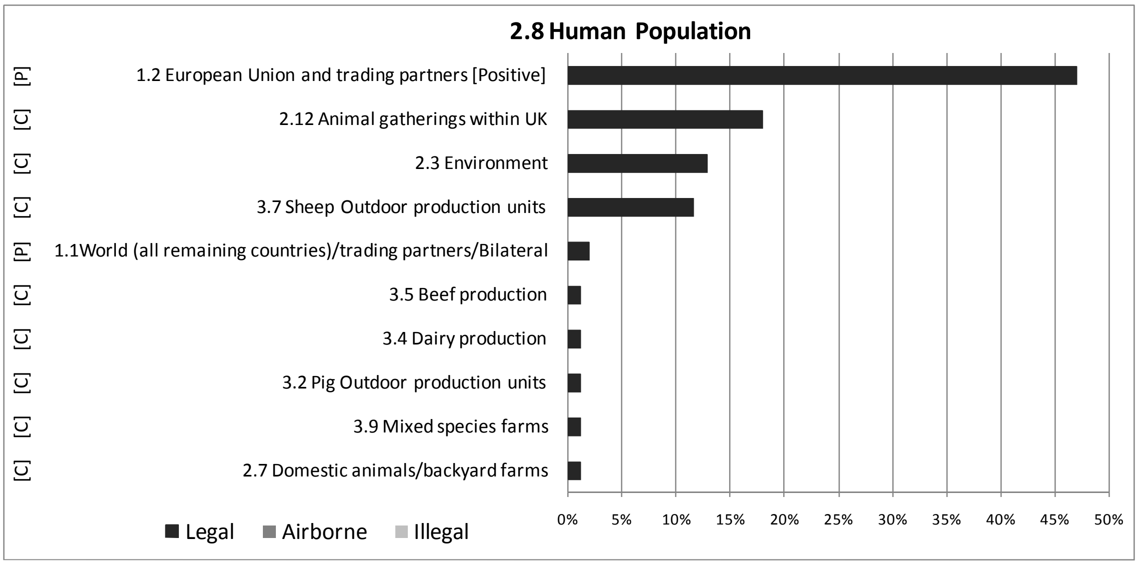

Figure 9.4 "2.8 human population" arc sensitivity analysis

[Key] Representing all process/events associated with the "2.8 human population" node in order of importance regarding their influence in the likelihood of system failure.

A top-down analysis of the outputs allows for a progression from an overview of the system to a state of increasing detail. This analysis of the output allows priorities to be defined at a higher level (node level) followed by the identification of key areas of intervention to tackle those priorities (arc level).

9.3.3 Disease sources

Outbreak pathways are significantly impacted by the disease source. Within this model three independent disease sources are considered. Figure 9.5 displays the relationship between the disease sources relative to their contribution to likelihood of an outbreak. The greatest threat, with 94.8% of exposure of FMDv to susceptible receptors, is due to "(EU positive)". Third countries contribute 5.2% of exposure, while laboratory escapes provide 0.003% to the overall exposure. These results indicate that free movements of cargo and people within the EU drive the risk of an FMD incursion thus confirming worries of international organs regarding the increase international mobility.

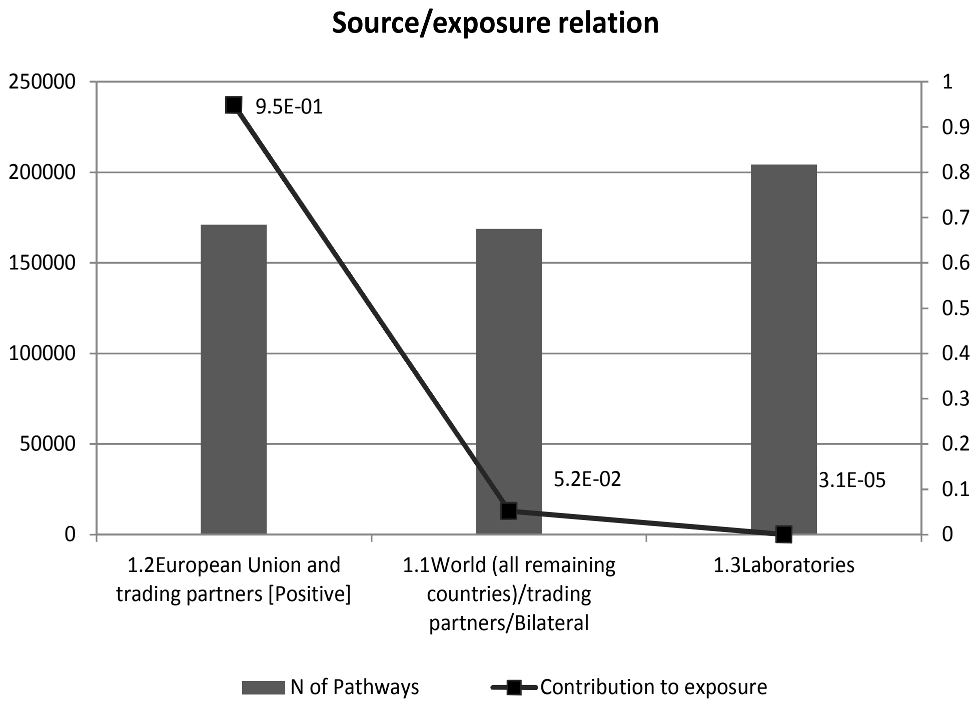

Figure 9.5 Comparison between disease sources

[Key] Relation between the number of pathways and contribution to likelihood of system failure: Left Y axis representing number of pathways; Right Y axis the contribution to likelihood of exposure (0 to 1).

9.3.4 Legal, illegal and airborne transmission

The application of the systemic risk model to FMD presents an evolution from the previous application (Chapter 8). This evolution is based on the capacity of the model to distinguish between the effects of illegal and legal activities and airborne transmission on system vulnerability. The network considers 694 *process/events* from which 302 represent movements associated with legal activities, 264 represent movements associated with illegal activities and 128 represent movements associated with airborne transmission of FMDv. This analysis is based on a sensitivity analysis targeting each of these movement types. From the results (Figure 9.6), legal movements have the highest impact on system performance with a 50% reduction of all BFR from *process/events* associated with legal movements, which caused a decrease of

82.7% in system vulnerability to an FMD incursion. In contrast, illegal movements display the lowest influence on system performance representing an increase in system resilience of just 0.056%. The increased control over airborne transmission of FMDv resulted in an improvement to system resilience of 26.3%. The significant difference presented by legal and illegal movements is difficult to explain. This difference may result from the adopted definitions to characterise them. The cornerstone of the character was definition of illegal movements as “non-compliant movements”. Therefore, in the absence of regulation these movements were considered legal thus making legal movements comparatively more frequent even though approximately similar numbers of legal and illegal *process/events* were available. The data also suggests that legal controls may be more effective for nodes closer to the source (i.e. introduction into the UK) though once in the country controls of EADs stop being a priority.

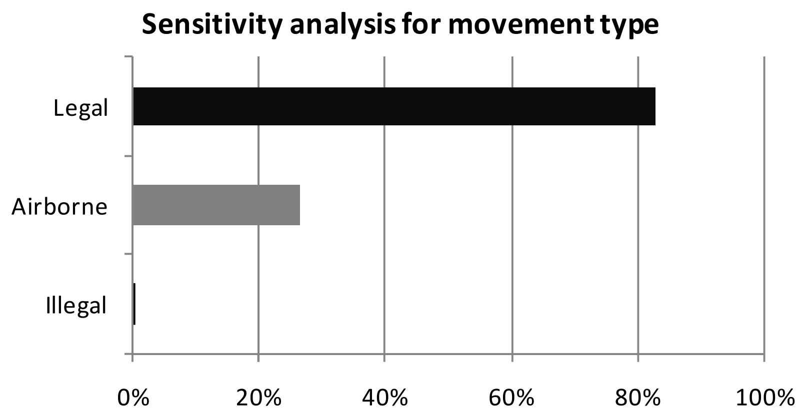

Figure 9.6 sensitivity analysis of movement types: legal, illegal and airborne transmission

9.3.5 Pathways length and the likelihood of an FMD outbreak

This analysis provides understanding of the drivers of risk in order to help development of sustainable risk management strategies. The risk analysis methods applied so far to develop risk mitigation strategies and improvement of the existing controls were based on a top-down risk assessment approach involving a combination of independent qualitative and quantitative models (Taylor, 2003; Peeler et al., 2006). This approach is defined here as the "complementary approach" as it assumes qualitative and quantitative models complement each other providing a complete analysis of risk. This involves using a qualitative model to develop an overview of the system and a quantitative model to assess specific incursion pathways. For systems that are well understood the complementary approach is effective in defining high risk introduction pathways, for example assessment of direct pathways such as live animals and germplasm imports (Sánchez-Vizcaíno et al., 2010; Bronsvoort et al., 2008). However, this top-down approach requires the assessors and experts to possess an understanding of disease introduction mechanisms (Freeze et al., 2005). Unfortunately, such knowledge is currently incomplete, as observed by the UK's 2001 FMD outbreak whose origin has never been confirmed (Scudamore, 2002). Similarly, of the 66 FMD outbreaks confirmed worldwide between 2008 and 2010 72% of the epidemiological investigations returned inconclusive views on the origin of the FMD virus (OIE, 2010). This significant knowledge gap compromises the insight generated by top-down approaches, which, may overlook significant pathways of introduction.

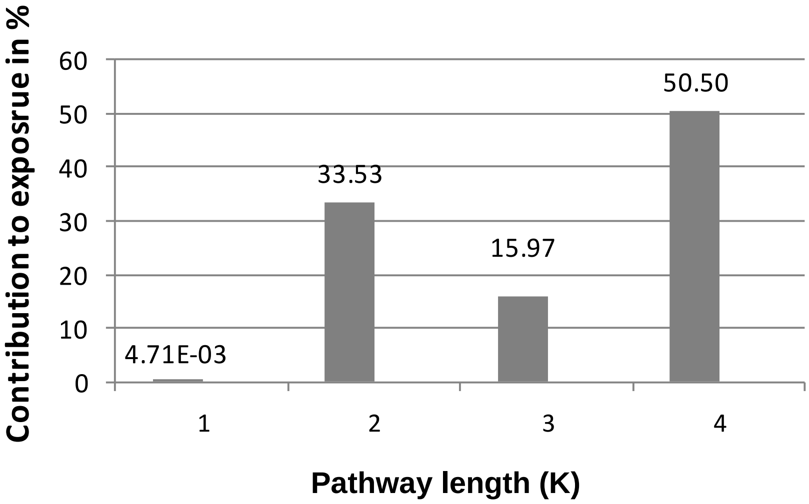

Figure 9.7 Comparison between pathway length and contribution to likelihood of system failure

Figure 9.7 describes the relationship between groups of pathways organised according to length and their contribution to FMDv exposure. Shorter pathways represent known pathways of exposure addressed in previous risk assessments while a void in literature exists where longer pathways are considered (Figure 9.7). The first column represents direct pathways of exposure (k = 1). These are direct transmission routes of the disease agent from source to receptor, expressed through movements of live animals and germplasm. There are 54 direct pathways identified by the model representing a contribution to overall exposure to FMD of 4.7E -3%. Based on this value these pathways are unlikely candidates to be the cause of future FMD outbreaks. In contrast, the longer pathways considered, resulting from various combinations of events (k=4), were identified in a larger numbers (512,137). These pathways represent a greater contribution (50.5%) to the risk of exposure to FMDv. There is a gap in literature regarding the study of longer pathways suggesting the majority of introduction pathways and the groups that contribute to them have not been addressed in prior assessments. This gap in literature may result from a combination of factors. First, conventional risk assessments that assess specific pathways of EAD introduction focus on a small number of pathways and apply resource and time intensive quantitative models. Considering that our model describes 544,067 pathways, developing a similar volume of pathways via conventional means would be resource prohibitive. Secondly, pathways evolved as a result of recent changes in the international panorama regarding movement of people and goods and therefore are not likely to have been assessed previously (Otte et al., 2004). Finally, as direct pathways are progressively identified and addressed the residual risk of exposure is transferred to the remaining indirect or unacknowledged pathways.

It is arguable that with continuous developments on the international trade panorama the conventional approach could remain adequate for understanding and assessing the likelihood of future EAD outbreaks. However, a full understanding of the system by considering all possible pathways of introduction regardless of likelihood or pathway size may provide greater value moving forward.

9.3.6 Controlling risk and intervention for improving protection against FMDv

In the same manner that changes in the international trade panorama have challenged the capacity to study the risk of EAD outbreaks, so have they challenged the capacity of countries to improve protection (EFSA, 2006). Conventional risk management focuses on applying controls to individual pathways. Due to the large number of pathways available, this process becomes highly inefficient as the targeting of a single pathway does not consider the effect of that intervention on the system as a whole. Our approach focuses on the relationship between system vulnerability and pathway components to reveal new opportunities for intervention. The influence a component i.e.

process/event, has on system vulnerability results from the quality of the controls and frequency of the movements associated with it but also from the number of pathways it is common too. An analysis that ultimately focuses on system vulnerability ensures that identified priorities reflect those of the system leading to more efficient interventions.

The results presented here focus on developing a list of priorities based on these principles. The format selected for the output manages the volume of outputs produced in order to guide a decision making body towards the identification of the process/events within the network system whereby control measures will produce the most significant risk reductions. We described these previously as the critical control points (CCP) of the system (Delgado et al., 2010).

Though the model successfully identified vulnerabilities in the system the development of a risk management strategy requires consideration of a wider range of factors, such as current legislation, trade agreements, economical impacts of implementing new controls and availability to improve control options. Therefore, this model provides yet one more source of information to support decision makers.

9.4 Conclusions

This is the first application of a system analysis based on a bottom-up approach to study the risk of introducing FMD in the UK. This involved building upon the systemic model applied to study CSF to ensure a comprehensive analysis of the multi-barrier system. This application resulted in the identification of priorities within the system where intervention is likely to improve UK's resilience to an FMD outbreak (Figure 9.2). Through comparison with previous assessments, this model provides insight on the limitations of conventional IRAs and of the risk mitigation strategies developed from them. The development of this model successfully:

- Provided a comprehensive analysis of the risks and mechanisms involved in the introduction of disease agents into the UK. This included an analysis of the influence of legal movements, illegal movements and FMD transmission characteristics to overcome the controls currently in place. Furthermore, it recognised the system's complexity, described as a network from which several interconnected pathways arise (Figure 9.1).
- Developed a comprehensive analysis of the interaction between the FMD virus and the multi-barriers system. This analysis establishes a link between the failures in individual barriers to FMD transmission and their influence in UK's vulnerability to FMD (Figure 9.2). This is a novel approach, which allows to develop a system of priorities defined as CCPs, where intervention is likely to produce the greatest improvement to UK's resilience against future outbreaks.
- The results identified the movements associated with the human population (2.8 Human population and 2.7 Domestic animals/Backyard farms) as those where improved control can contribute significantly for improving UK's resilience against an EAD (Figure 9.3). Furthermore, it displayed that longer pathways (K =4) pose a greater threat than direct pathways (K=1) (Figure 9.7). This suggests the current residual risk results from complex introduction pathways, which involve the human population. These pathways contrast with the focus of conventional quantitative models (that focus on direct pathways associated with livestock industry or retail industry, such as import of live animals, germplasm

and meat goods). Thus, the model identifies pathways of exposure overlooked by conventional methodologies.

- Provided an argument against the conventional approach to developing IRA and the mitigation strategies resulting from them. The analysis supported the development of policies that focus on improving the system resilience to FMD, as opposed to addressing individual pathways of exposure, provide for prioritisations that are more accurate. Such an approach provides the insights to improve further UK's resilience against an EAD outbreak.

10 EAD INCURSION AND LIVESTOCK EXPOSURE – APPLICATION TO CSF AND FMD

The analysis of the pre-outbreak (pre t_0) phase involves the two applications of the model to study the resilience of the multi-barrier system against the incursion of CSF and FMD. Despite the differences in the network model and parameters characterising inter-node movement, it provides the opportunity to draw conclusions from the output resulting from both applications. This analysis of the outputs focuses on: (i) the comparison of outputs to identify the priorities and CCP, which represent vulnerabilities and opportunities for improving the system that are consistent across diseases and (ii) develop understanding of the influence of low probability events in causing the failure to detect and eliminate the disease agent before exposure to livestock.

10.1 Disease incursion trends of CSF and FMD

The expert-based systemic models provide an analysis of the system to allow for the identification of the movements and features that drive the risk of exposing livestock to an EAD. The results produced by the model are not consistent with what are apparent concerns of the animal health community. Using the scenario-based assessments produced in the last decade as a barometer of these concerns, these show a focus on issues associated with the livestock industry (De Vos et al., 2004; Sánchez-Vizcaíno et al., 2010; Bronsvoort et al., 2008; Martínez-López et al., 2009). The scenario-based models applied focus mainly on the importation of live animals and other movements associated with the livestock industry, e.g. germplasm, feed and livestock lorries. The systemic models display a different trend, which supports that direct movements from source to farms (Figure 10.1) and through the borders inspection posts, which include the trade associated with the livestock industry, pose little influence on system behaviour (Figure 8.3 and Figure 9.3). Instead, the results display a trend that is in line with increase in freedom for the movement of people and goods across borders (Otte et al., 2004; EFSA, 2006). These suggest the greatest sources of risk are associated with the human population (Figure 8.3 and Figure 9.3). The results also highlight the emerging role of domestic animals and farm animals not produced for slaughter and of animal gatherings. Such a trend suggests the controls implemented in the livestock industry are effective in controlling exposure to an EAD agent and supports the recent concerns associated with over exposure to EAD, resulting from the free market agreement (Otte et al., 2004; EFSA, 2006). Therefore, advising the improvement of the controls on imports not directly associated with the livestock industry is relevant to improve the current resilience of the multi-barrier system against the incursion of EAD.

10.2 Low probability events

The development of the IRA model addresses Defra's recommendation to study the influence of low probability events (LPE) on UK resilience against the incursion of an EAD and its exposure to livestock. The exact definition of the proposal was the "*analysis of risks from low/medium probability risk pathways (...) to identify and assess (...) scenarios if a sequence of low probability events occurs, taking into account current levels of risk management*" (Defra, 2011a). The need to define LPE as sequences of unlikely events is not exclusive to the introduction of EAD. Instead, this is a common challenge for any disaster prevention system that applies the systemic property of redundancy as a protective measure against failure of individual protective barriers (Reason, 1997; Pidgeon and O'Leary, 2000). Recent high profile examples associated with LPE are the onset of the financial crisis and BP oil spill in the Gulf of Mexico (BP, 2010; Tanneeru, 2009). A characteristic of LPE is the surprise caused by failure. However, once analysed its causes may become apparent and future incidents avoided (Reason, 1997).

10.2.1 Low probability events excluded from the scope of conventional RA methods

Import risk assessments to date have focused on the application of conventional risk assessment models (Taylor, 2003). These apply a *top-down* (TD) approach to model development. The top down approach creates a dependency of the model to the assessor knowledge base, regarding the considered scenarios of exposure (Freeze et al., 2005). This exposes the model to a number of biases in scenario selection. Thus, making it vulnerable to motivational biases, influencing the assessment to focus on scenarios that are of the interest of the assessor, and availability which influence focus on the scenarios that are readily available in the experts mind and excluding less present ones (Cooke, 1994; Tversky and Kahneman, 1974). Most importantly, a top-down approach excludes all scenarios that are unknown to experts. Consequentially, conventional RA models tend to focus on mainstream scenarios whilst excluding outliers. This phenomena is observable in scenario-based quantitative import risk assessments (IRA), where from the 14 models identified in literature six assess EAD introduction through the importation of live animals to farms (De Vos et al., 2004; Martinez-Lopez et al., 2008; Bronsvoort et al., 2008; Hoar et al., 2004; Jones et al., 2004; Wahlstrom et al., 2002). LPE are by definition outliers, therefore conventional risk approaches fail to assess them.

10.3 Definitions of low probability events

Within the animal health community, there are two standing interpretations of the definition of low probability events. A first interpretation is consistent with the work developed in the area of organisational risk management and systems safety. Here low probability events represent *the coincidental sequence of barrier failure-causing events, which undermines the redundancy of the multi-barrier protection system. Thus, allowing for undetected transmission of EAD, leading to its exposure to livestock* (Reason, 1997; Pidgeon and O'Leary, 2000; Reinach and Viale, 2006). This definition agrees with the research objective set by Defra that suggests focussing on “a sequence of low probability events” (Defra, 2011a). The influence of such events has been acknowledged in the hypothesis for the origins of the CSF outbreak of 2000 (Gibbens et al., 2000; Sharpe et al., 2001).

A second interpretation adopts a definition of LPE assuming exposure as the results from *one isolated barrier failure-causing event that, whilst infrequent has the capacity to enable exposure of livestock.* These are infrequent barrier failures, which may have the capacity to undermine the efficacy of the protection system, in detecting and eliminating the disease. Examples of reports referring to low probability events under this definition are the possible environmental release of FMD from Pirbright in 2007 (Defra, 2007a) or the avian influenza outbreak in Suffolk in 2007 (Defra, 2007c). In this last case the epidemiologic report, assigns its cause to an unspecified low probability event: “difficulty in identifying the precise source is probably in part due to the fact that this is a very unlikely occurrence and an isolated event that occurred probably in January” (Defra, 2007c).

10.3.1 Studying sequences of events leading to an EAD outbreak

The network model provides a description of the components included in each pathway, creating the opportunity to assess the contribution of different exposure scenarios to the overall risk of an EAD incursion. The number of scenarios of exposure assessed for CSF and FMD depend on the network generated to represent the system. Due to differences in transmissions mechanisms existing between CSF and FMD and the increase detail regarding movement types considered, the network model grew in the number of nodes and in the level detail associated with each *process/event* between applications. As a result, the number of scenarios identified increased from the first modelled disease (CSF) to the second one (FMD). Increasing from 54,663 introduction scenarios with a length of up to $k = 5$ for CSF, to 8,373,788 scenarios up to a similar length identified for FMD.

The description of the pathways of introduction allowed for discriminating between pathways of different lengths and comparison against scenarios described in literature. This resulted in the division of the exposure scenarios into two groups. Network theory divides scenarios according to pathway length, separating them as direct pathways ($k = 1$) and indirect pathways ($k \geq 2$) (Borrett and Patten, 2003; Newman, 2003). However, considering the existing body of import risk assessments, a different division is proposed:

Simple incursion scenarios (SIS) include introduction pathways with a length $k \leq 2$. These scenarios represent activities allowing for direct introduction of EADs into a livestock farm, such as live animal and genetic material imports or the airborne introduction of FMD (Donaldson et al., 1982; Martinez-Lopez et al., 2008; Sutmoller and Wrathall, 1997). Also included as SIS are indirect but simple pathways, such as the return of contaminated livestock trucks and accidental virus release to the environment from laboratories, which involves environmental contamination and subsequent exposure to livestock (De Vos et al., 2004; Anderson, 2008).

C*omplex incursion scenarios:* (CIS), include longer pathways (k ≥ 3), representing scenarios caused by multiple interactions between system components, such as the scenario put forward as possible cause of the 2000 CSF, 2001 FMD and 2007 HPAI outbreaks (Gibbens et al., 2000; Sharpe et al., 2001; Defra, 2007c; Scudamore, 2002). These represent a group of scenarios that due to their complexity are harder to forecast.

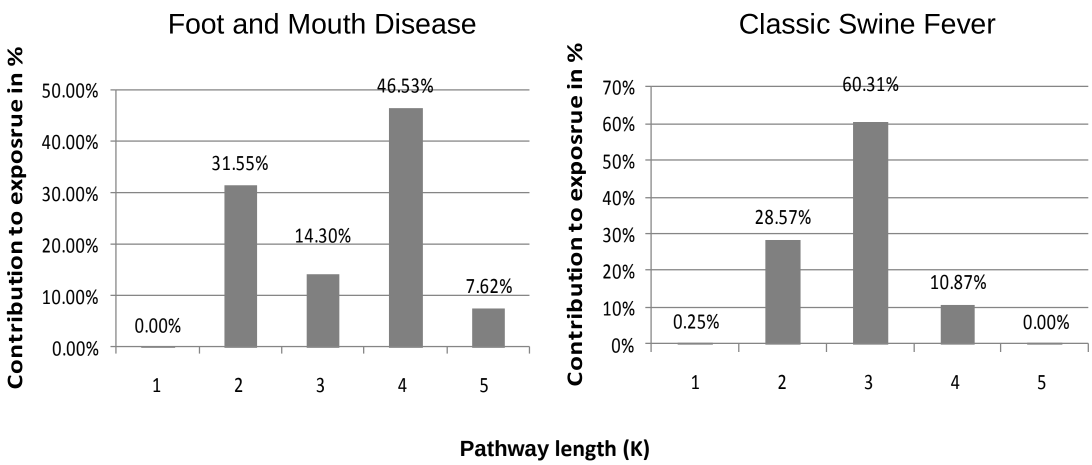

Figure 10.1 The contribution to overall risk of exposure regarding pathway length for FMD (left) and CSF (right)

In the network model, a *process/event* represents a movement of EAD controlled by one of a set of imperfect barriers, whose failure can be triggered by an event. SIS represent scenarios of exposure composed of one or two process/events. Therefore, failure to detect and eliminate the EAD agent in these scenarios results from the occurrence of one or two simultaneous barrier failure events. In contrast, CIS represent scenarios composed of at least three process events. Therefore, failure to detect and eliminate the

EAD agent in these scenarios results from the coincidental occurrence of three of more of these barrier failure-causing events.

There is a bias of RA towards focussing on SIS (De Vos et al., 2004; Morley, 1993; Yu et al., 1997; Martinez-Lopez et al., 2008; Sánchez-Vizcaíno et al., 2010; Bronsvoort et al., 2008; Hoar et al., 2004; Jones et al., 2004; Wahlstrom et al., 2002; Astudillo et al., 1997; Martínez-López et al., 2009; Weng et al., 2010). However, these represent only a small fraction of all available introduction pathways, more specifically 0.05% and 0.02% of all available scenarios for CSF and FMD, respectively. Thus, suggesting that the majority of the introduction scenarios remain unstudied. Figure 10.1 displays the overall risk of exposure presented by pathways with different lengths for the FMD and CSF assessments. In both assessments SIS ($k \leq 2$) are responsible for ≈ 30% of the overall risk of exposure. Where direct pathways of introduction ($k = 1$) present a negligible contribution to the risk of exposure, 4.44E-3% for FMD and 2.51E-1% for CSF. In contrast, CIS ($k \geq 3$) are responsible for roughly 70% of the overall risk of exposure in both assessments. The definition of CIS is consistent with that of LPE as a sequence of events (Reason, 1997; Pidgeon and O'Leary, 2000), which leads to the assumption that LPE are represented within the group of CIS allowed by the multi-barrier system. This suggests LPE may be responsible for 70% of the overall risk of exposure.

10.3.2 The dangers of partial information when developing risk mitigation measures

The bias towards focussing on SIS may be justified by a combination of factors that have influence over the development of RA. Firstly, assessors, experts and governing bodies alike only recently became aware of the existence of LPE (Anderson, 2002;

Gibbens et al., 2000; Defra, 2007b). This results from the complexity and at times erratic combination of interactions that compose CIS (Pidgeon and O'Leary, 2000), which allow the disease agent and the barrier failures that enable them to go undetected by epidemiological reports developed for past outbreaks. Secondly, these events may have been exacerbated by the current changes in international policy allowing a free movement of people and meat goods across borders (Otte et al., 2004; WHO/FAO/OIE, 2004), creating complex pathways that play a significant role in disease introduction (Morris, 1995). The acknowledgement of LPE as a potential threat represents an important step in recognising that so far the animal health community possesses partial knowledge over the causes of EAD outbreaks. The relation between partial knowledge of the system and the conventional approach to assessing risks explains the bias towards known exposure scenarios. For example, consider the following comparison between the SIS and CIS generated by the FMD assessment. The assessment produced 1672 SIS, responsible for 31.5% of exposure risk and 8,373,788 CIS responsible for 68.5%. The conventional approach guiding the development of IRA focuses on studying individual scenarios identified as a likely threat. Based on this approach the bias towards SIS is justifiable as these have on average a greater individual contribution to risk than CSI (31.55% / 1672 > 68.45% / 8,373,788). However, by understanding risks based on a systemic perspective, one must acknowledge that, the risk of exposure results from the occurrence of any one scenario allowed by the system. Considering this, the CIS pose 2.17 times greater risk than pathways included as SIS and by consistently overlooking them, risk assessments have ignored the current greatest contributor to the residual risk of exposure.

10.3.3 Developing risk managing strategies that tackle the risk posed by CIS

The acknowledgement of CIS as a threat expands the available insight regarding the scenarios of incursion responsible for the introduction of EADs into the UK. Furthermore, it symbolises a more profound understanding of system behaviour and of exposure scenarios. This expansion in knowledge acknowledges a system that is both larger and more complex than previously considered (Morris, 1995).

RAs influence risk management strategies. Therefore, strategies and policies supported by the insights produced with conventional RAs present the limitations that arise from their narrowed perspective. Thus, these strategies and policies can overlook characteristics of the system, resulting in a failure to manage significant drivers of exposure. In contrast, the models developing a systemic perspective take into consideration SIS and CIS, moving the understanding of risk from focussing on isolated scenarios of introduction to focusing on a network of connections encompassing a vast number of scenarios. A network entails that the large number of pathways result from the interaction of a smaller number of components, where each component or even each interaction between components may participate in multiple exposure scenarios (Murthy and Krishnamurthy, 2009; Pearce and Merletti, 2006; Newman, 2003). This allows moving from addressing individual scenarios with disregard for their effect on system behaviour to addressing multiple scenarios based on the effect the common components have on system behaviour. Consequentially, risk prioritisations resulting from these models reflect the needs of the system and address all scenario types described by the model, i.e. SIS and CIS, simultaneously.

10.4 Low probability event as an infrequent but high-impact events

The alternative definition of LPE describes them as isolated infrequent barrier failure-causing events, which have a significant impact over UK vulnerability to the system. There is no reference in literature regarding the existence and influence of such events in multi-barrier systems. In fact, we suggest the example provided alongside the definition (Section 10.3), the epidemiologic report developed for the HPAI outbreak of 2007, incorporates an erroneous interpretation of the LPE (Defra, 2007c). In the report, the conclusions produced hold responsible an isolated event for causing the outbreak. However, this same document describes that scenario of exposure as involving an import of turkey breasts with an undetected contamination, complacent waste disposal in the transformation plant and the influence of wild life in the exposure of farmed animals. Thus, although the conclusion highlights one isolated event, the scenario described includes that event into a sequence of events that is consistent with the definition of CIS.

Nonetheless, if isolated LPE exists, an approach to develop priorities that based on the influence process/events have on system behaviour, as presented by the presented model, will detect them and prioritise them in comparison with the remaining process/events driving exposure.

10.5 Tackling low probability events

The formats developed to communicate focuses on the influence process/events have on system performance. This approach detects influential events whether this are part of a wider sequence of events, SIS and CIS. Defining priorities according to these parameters allows exposing opportunities to improve system resilience, and controlling the effect of LPE, independent of definition. Therefore, it represents a systemic and cost-efficient approach to develop priorities.

10.6 Conclusions

The expert-based systemic models develop a comprehensive analysis of the multi-barrier system. These models consider the entire system and all pathways of exposure associated with the introduction and exposure to of livestock to EAD. In doing so, the model allows for the detection of vulnerability and trends in transmission, which are beyond the scope of qualitative models, as these do not consider specific pathways of exposure and models focussing on one or a small number of exposure pathways. The application of the expert-based systemic models achieved the following:

- The identification that pathways of exposure, that are not associated with the livestock industry but that play a significant role in the introduction of EAD into the UK and may play a significant role in future EAD outbreaks.
- It develops an analysis of LPE and of the influence this pose in system behaviour. This resulted in the division of pathways of exposure into SIS and CIS, where LPE are include in the latter category. Furthermore it identifies that the introduction of CSF or FMD into the UK through any one CIS is two times more likely than the introduction through a SIS. Thus, it suggests that LPE pose influence in the behaviour of the system and are a likely to play a role in the future EAD outbreaks.
- These results suggest that conventional risk assessment methods have been effective in controlling exposure. However, at this time exposure of livestock to an EAD results from complex pathways of exposure, which are not directly

associated with the livestock industry. Therefore, these are often difficult to predict and thus excluded from conventional assessments, confirming the need for a systemic assessment to improve further the resilience against the incursion of EAD into the UK.

10.7 SUMMARY OF THE FINDINGS FOR THE PRE-OUTBREAK (PRE T_0) PHASE

The research presented in Part 2 of this thesis, developed a comprehensive analysis of pathways of introduction for CSF and FMD incursion into the UK. The work focuses on analysing transmission during the pre-outbreak (pre t_0) phase of an EAD outbreak. Specifically, analysed transmission and exposure of livestock to CSF or FMD. Claims of novelty presented within these chapters are associated with insights gained on the cause for EAD introduction (Chapter 6, 7, 8, 9 10). Whilst claims of novelty associated with the application of systemic models are discussed further in Chapter 11. From this research, we claim the following.

The research developed and applied a novel method, to identify vulnerabilities in the multi-barrier system to prevent EAD introduction and exposure to livestock. The models consider all pathways of exposure available in the network that can cause the exposure of livestock to CSF or FMD (Chapters 8 and 9, respectively). It achieved this by applying a computer model to generate the pathways of exposure that enables the model to consider pathways of exposure excluded for risk assessments available in the prior art (Section 2.2). Thus, it generated new insights to support the development of policy interventions.

The comprehensive analysis of the multi-barrier system generated new insights that resulted in the identification of EAD transmission trends and vulnerabilities in the system. The outputs suggest the following:

- The current risk of exposure is linked to pathways not directly associated with the livestock industry (Section 10.1). The identification of this trend supports the current concerns with the free movement of people across borders and personal imports goods and animals (Otte et al., 2004; EFSA, 2006). This is supported by the result of the first level of the sensitivity analysis presented in Figures 8.4 and Figures 9.3.

- The most significant vulnerabilities in the system are associated with movements concerning the human population. Model application identified specific vulnerabilities in the system for CSF (Figure 8.5) and FMD (Figure 9.4). This represent the CCP of the system, and describe specific process/event where intervention is likely to improve significantly UK's resilience to future EAD outbreaks
- The analysis between legal and illegal movements and airborne transmission of FMD (Figure 9.6), present legal movements as a key concern (82.7%) whilst illegal movement present minimal influence in the EAD introduction (0.056%). This suggest that to further improve protection, the focus should be in improving the policies currently in place as opposed to improving their enforcement.

The development of this research provided insights on the influence of low probability events (LPE) in UK's vulnerability to EAD.

- The outputs produced by the models provide insights on the multi-barrier system's vulnerability to LPE. These are introduced as complex incursion scenarios (CIS), representing complex sequences of process/events establishing a link between an EAD source and livestock animals. The output reveals that introduction through a specific CIS is unlikely, however due to the large number of them available in the network, the introduction of CSF or FMD through any one CIS is more likely than by any one simple introduction scenario (SIS) – SIS are the pathways of exposure conventionally assessed by scenario-based models (Chapter 10). Thus, the work develop identifies LPE pose significant influence in the exposure of livestock to EAD.

This research adopts the same format to communicate the output presented in Chapter 5 (Section 5.3). The outputs are communicated through a format composed of a progressively more detailed analysis of the system. A first tier ranks the features posing the greater influence in the transmission of EAD (Figure 8.4 and Figure 9.3) and a second tier identifies process/events presenting CCP for efficient intervention in the system (Figure 8.5 and Figure 9.4) . Lastly, a third tier exposes the context associated with the CCP to providing information regarding the causes for barrier failure (Section 8.4.1). This format of communication provides access to risk analysts and policy makers to the outputs. These are organised to provide an easy identification of the drivers of exposure and causes of barrier failure, thus providing the information to support the development of decision that improve protection against the livestock exposure to an EAD agent.

Lastly, this research provides insights on efficient strategies to improve the performance of the multi-barrier system. This research suggests the development of strategies that do not address specific pathways of introduction, but instead supports the development strategies that focus on process/events with a significant influence on system behaviour. This is supported by the approach used to develop the study of the multi-barrier system (Chapter 6), the results presented in (Figure 8.5 and 9.4), and specifically by the new insights on how to control the influence of LPE in UK's vulnerability (Section 10.5).

The research presented in Chapter 6, 7, 8, 9 and 10 develops a comprehensive analysis of the mechanisms of incursion and preventative controls associated with the introduction of EAD into the UK. The outputs produced have expanded in quantity and quality the insights available in data and literature from past outbreak and predictive models available in the prior art (Chapter 8 and 9). Furthermore, the research has successfully generated insights on the knowledge gaps associated with the research objectives presented in Section 2.6 (Chapter 10). Thus, it is safe to assume the insights generated by this research have expanded the knowledge available to support policy decision (Chapters 8, 9 and 10). The information, now available provides insights to improve the UK's resilience to future EAD outbreaks.

11 DISCUSSION

This chapter provides an overarching discussion of this research. Here the core themes are discussed and claims for novelty introduced and evidenced. The chapter concludes with a critical analysis of the work. Conclusions are drawn in Chapter 12.

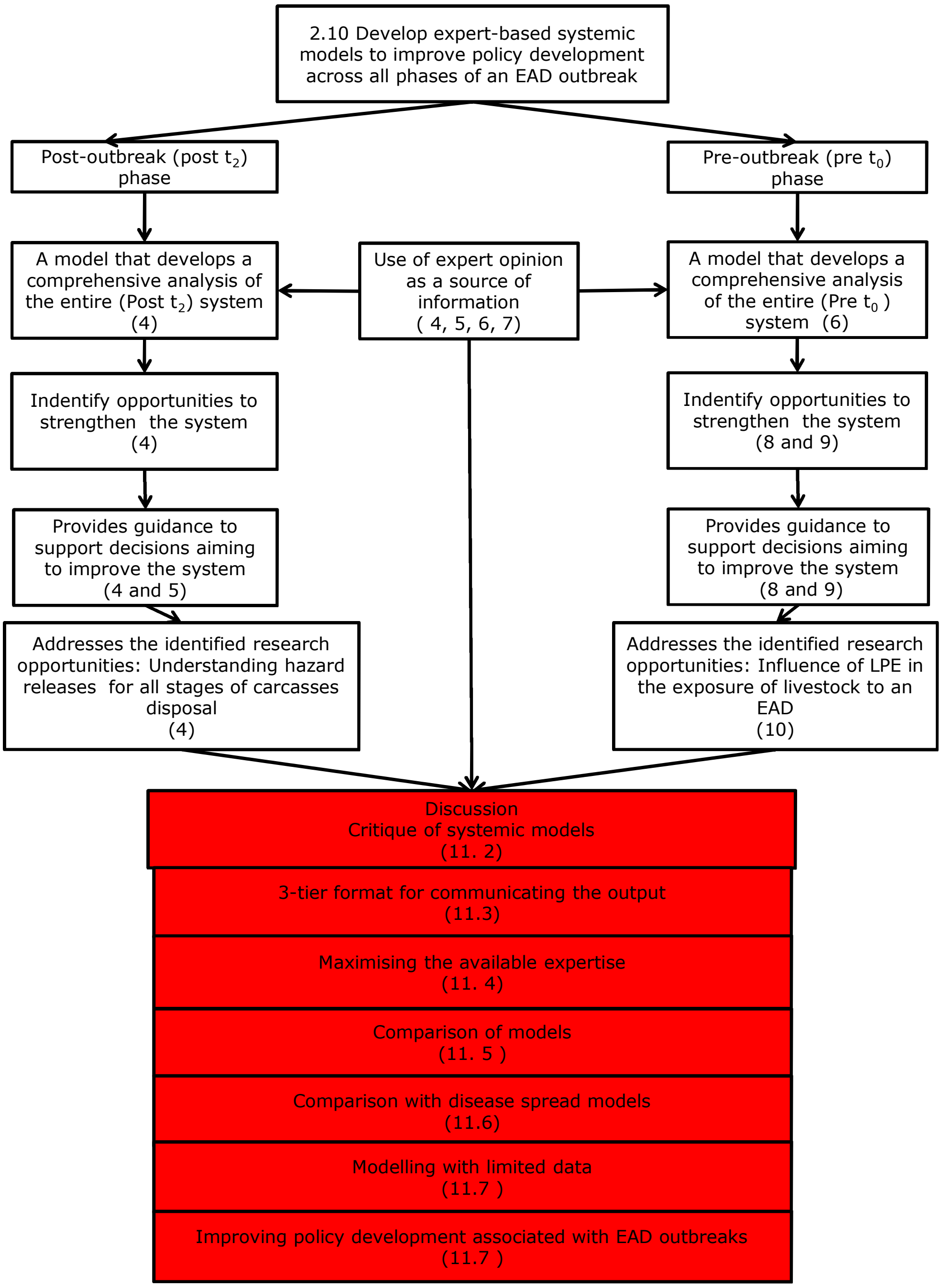

Figure 11.1 Discussion

[Key] Red boxes describe the topic addressed in the discussion. Numbers represent the sections dedicated to each topic.

11.1 Introduction

The aim of this chapter is to discuss the results presented in Chapters 4, 5, 8, 9 and 10, in relation to the prior literature and the implications of adopting systemic models to improve the decision-making capacity to develop policies associated with EAD. Firstly, I discuss the characteristics of systemic models that allow the improved quality of the information available to support policy interventions (Section 11.2). Then a format for communicating outputs that improves visualisation of system vulnerabilities (Section 11.3); the use of expertise in systemic models (Section 11.4) and; the role of systemic models in the range of available tools (Section 11.5). Claims of novelty from this research, in addition to the insights produced for the post outbreak phase (Chapters 4 and 5) and pre-outbreak phase (Chapters 8, 9 and 10), are associated with the superiority of systemic models to identify system vulnerabilities and patterns of system behaviour, to support policy interventions for managing EAD; a format for communicating outputs that supports development of efficient policy interventions and; maximisation of available expertise.

11.2 Critique of systemic models to EAD

In this section, I critique systemic models applied to EAD, in light of the research presented in Chapters 4, 8, 9 and 10 and models available in the prior art. This section focuses on their capacity to develop improved insights on system behaviour and system vulnerabilities to inform policy developments to reduce UK's vulnerability to EAD. In the prior art, associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases of an EAD outbreak, insights on the behaviour of EAD and on the vulnerabilities of the system of controls resulted from the development of expert based and scenario based models (Section 2.2, 2.3). However, expert based and scenario based models present limitations to their analytical capacity, which restricts the scope of the assessments produced (Section 2.4), making them unable to provide comprehensive analyses of the systems associated with the two outbreak phases (Dangerfield and Morris, 1992; Freeze et al., 2005; Zio, 2009; Grundke, 2010). As a result, used individually, expert based and scenario based models provide insights on system behaviour and on system vulnerabilities, based on incomplete information, which may not be accurate.

Taylor, (2003) and Peeler et al. (2006) suggest that using the expert based and scenario based assessments together can overcome the individual limitations of the models available in the prior art (Section 2.5). This is a top-down approach, which uses expert-based models to develop high-level priorities and scenario based models to study pathways of exposure associated with those priorities. Work developed in other areas of risk analysis exposes weaknesses in this approach (Dangerfield and Morris, 1992; Freeze et al., 2005; Zio, 2009; Grundke, 2010). Priorities identified by the experts-based assessments will influence the subsequent scenario based analysis. If information on the behaviour of the system is limited, as is for the pre-outbreak and post outbreak phase (Section 2.1.2), high-level priorities can overlook significant but unknown risks and pathways of exposure. As a result, priorities defined through the conventional approach can overlook significant vulnerabilities in the system (section 2.5). Standing examples are the research opportunities identified in the literature review (Section 2.6). A summary of the research opportunities of each phase follows:

- Risk assessments of the post-outbreak phase in the prior art have failed to assess in detail the disposal activities performed on the farm, even though three of the four high category environmental contamination incidents recorded are associated with these activities (Environment Agency, 2001).

- Risk assessments of the pre-outbreak phase in the prior art have failed to assess the influence of low probability events (LPE) in UK's vulnerability to EAD, even though epidemiological reports identify LPE as possible introduction routes for the CSF (2000), FMD (2001) and HPAI (2007) outbreaks (Gibbens et al., 2000; Sharpe et al., 2001; Defra, 2007c; Scudamore, 2002).

In this thesis, I introduce and apply to the pre-outbreak and post-outbreak phases, a modelling technique that overcomes the limitations of the models in the prior art. Systemic models focus on developing comprehensive analysis of the entire system. The results presented in Chapters 4, 5, 8 9 and 10 suggest these models improve the information available on system behaviour and improve our understanding of the breadth and depth of the system. I claim systemic models achieved in expanding the quantity of information available by developing analyses of the entire system; the quality of information available by minimising the influence of expert bias and preconceptions in the definition of priorities and; detect patterns of system behaviour that can influence the systems vulnerability to an EAD, generating insights for efficient policy intervention solutions.

11.2.1 Expanding the quantity of data available

Systemic models expanded the number of pathways of exposure assessed for the two outbreak phases by considering all pathways available in the system (Sections 4.2 and 6.3). The expert based and scenario based models in the prior art present limitations in scope, which do not allow them to develop an analysis of the entire system (Sections 2.4 and 2.5). Qualitative models do not represent specific pathways of exposure (Section

2.4). Scenario based models ""*adopt certain characteristics of event tree analysis, but systematically limit the number of (...) combinations*" (Freeze et al., 2005), thus reducing the number of pathways of exposure assessed (Section 2.4). As a result, the models available in the prior literature to study the pre-outbreak and post-outbreak phases develop incomplete images of the systems, which consider a fraction of the pathways of exposure available.

Systemic models expanded the number of pathways of exposure analysed for the two phases. The models were developed according to the principles of systemic modelling, ensuring the development of comprehensive analyses of the systems (Murthy and Krishnamurthy, 2009; Carré and Singer, 2008; Freeze et al., 2005; Newman, 2003). A defining characteristic of systemic models is a predefined focus on assessing all pathways of exposure and events that influence the EAD transmission (Section 2.1.4). Examples from the research presented here are:

- Results presented in Chapter 4 describe a comparative analysis of the all options available for carcasses disposal and of all stages of disposal considered for each option (Figure 4.3). For each stage of disposal, a suit of available pathways is assessed (Figure 4.4 and Figure 4.5). Thus, the systemic model assessed all pathways of exposure theoretically available in the system.
- Results presented in Chapter 8 and 9 display a network of connections that includes all entities influencing the introduction of EAD into the UK (Figure 8.1 and Figure 9.1). The models analyse the interactions between those components ensuring that all pathways of exposure (theoretically available) to introduce CSF and FMD into the UK are assessed (Section 6.3).

This characteristic of systemic models allows them to overcome the limitations in scope associated with models in the prior literature, which either do not consider pathways of exposure or focus in a small number of them (Section 2.4). The results presented in Chapters 4, 8 and 9 describe that systemic models develop a comprehensive analysis of the entire system and provide for an analysis of all pathways of exposure to EAD (Section 4.3.1, 8.3 and 9.2.5). As a result, applications of systemic models assessed all drivers of exposure associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases, thus expanding the quantity of information available to intervene in the system.

11.2.2 Minimising the influence of expert biases

Systemic models minimise the influence of prior knowledge and biases in the outputs produced, allowing them to detect vulnerabilities previously overlooked. The expert based and scenario based models, available in the prior literature, follow a top-down approach to model development. Models developed through this approach are vulnerable to prejudices on system behaviour and system vulnerabilities (Section 2.4). As stated by (Freeze et al., 2005) in conventional "*top-down approaches, end-point consequences are postulated and then the mechanisms by which these states may be reached are considered*" (Section 2.4). Specifically, prejudice biases the vulnerabilities identified by expert based assessments and the selection of the pathways of exposure analysed in scenario based assessments (Section 2.4). As a result, the conventional models to develop risk assessment of EAD fail to identify events driving exposure that are outside the concerns of the risk analysts and experts supporting the assessments, thus compromising the accuracy of the vulnerabilities identified.

Here, we suggest a modelling approach that minimises the influence of prejudice in the output. Systemic models consider all factors influencing transmission regardless of their preconceived contribution to EAD transmission (Murthy and Krishnamurthy, 2009; Carré and Singer, 2008). Here, a bottom up approach that ensures the system behaviour emerges from the pathways of exposure assessed (Section 4.2 and 6.2). As a result, systemic models develop analyses of systems, which are minimally influenced by prior beliefs and motivational biases (Dangerfield and Morris, 1992; Freeze et al., 2005; Zio, 2009; Grundke, 2010). The results presented support this claim and the application of systemic models succeeded in detecting drivers of exposure that have a significant impact on system behaviour, which were overlooked by previous assessments. Examples from the research presented here are:

- Results presented in Chapter 4, for the post-outbreak phase of an EAD outbreak describe that the disposal activities performed on farm (on-farm 3, 4a, 4b, 6a and 8a) pose a high level of risk of exposing the environment and to the livestock and human population to hazardous agents (Figure 4.3). The level of risk is comparable to that of disposal through pyres and uncontrolled burial of carcasses (process 3, 4a, 4b and 5). Assessments available in the prior art focused only on the stage of disposal where processing of carcass occurs (DH, 2001; Spouge and Comer, 1997b) (Section 2.3), whilst overlooking the impact of the activities performed on farm.
- Results presented in Chapter 8 and 9, relating to the pre-outbreak phase of an EAD, identify a set of pathways of exposure contributing the most to UK's vulnerability to EAD, which have not been assessed by the scenario based models in the prior art (Section 2.2.3). For example, the interaction matrices (Figure 8.2 and Figure 9.2) classify direct movements from source to receptor (e.g. import of livestock and semen) as not influential in the system

vulnerability. These are the pathways associated with scenario based models (Section 2.2.2). Instead, the systemic models (Figure 8.3 and Figure 9.3) identify the influence of the human population, domestic animals/backyard farms and animal gatherings in enabling introduction and exposure of EAD, claiming that exposure through pathways not associated with the livestock industry pose the greatest concern (Section 10.1).

Systemic models adopt a framework that provides for an unbiased comparative analysis of the pathways of exposure according to their influence on the system's behaviour (Section 4.2 and 6.2). This characteristic reduces the expert's influence in defining the system behaviour and its vulnerabilities. The results suggest systemic models have an improved capacity to identify the system's vulnerabilities. These are described as the critical control points (CCP) of the system (Delgado et al., 2010) and are the pathways of exposure and process/events where intervention is likely to produce a greater reduction in the risk exposing livestock to an EAD (Section 4.3.1, 8.4.1 and 9.3.2). Thus, the systemic models provide an increase in the quality of information available to support policy interventions.

11.2.3 Identifying patterns of system behaviour

Systemic models provide an analysis of the system that focuses on developing an understanding of the system's behaviour. The models available in the prior art, expert based models (Section 2.2.1, 2.2.2 and 2.3.2) and scenario based models (Sections 2.2.2 and 2.3.1), provide incomplete characterisation of the system and therefore fail to provide a comprehensive analysis of its behaviour (Section 2.4). Here, we advance on the prior art by introducing models that provide a description of the entire system, considering its boundaries and the role of its components in the exposure of EAD to susceptible receptors. Thus, systemic models provide a framework that represents the system in its entirety and accounts for the interaction of its components (Section 4.2 and 6.2). The subject of system definition was reviewed in Section 1.3, resulting in representations of the systems that are unique to the outbreak phase analysed. Examples from the research presented here are:

- Results described in Chapter 4 and 5, describe the disposal options as a chain of five independent environmental releases of hazardous agents (Figure 4.4 and Figure 4.5). Here it acknowledges that each stage of disposal is independent and impacts of disposal from one stage do not influence the next. However, it also considers that some disposal stages are common to multiple disposal options (Figure 4.2). Therefore, the impact caused by the disposal of carcasses in these stages influences a range of disposal options.
- Results presented in Chapter 8 and 9 describe the system involved the introduction of EAD into the UK and the multi-barrier system of controls to prevent it, as a network (Figure 8.1 and 9.1). This representation of the system acknowledges that pathways of exposure result from the intricate and complex interactions between system components.

Systemic models develop an analysis of the system components, inserted in a framework that aims to provide an accurate description of their real live behaviour. This approach allows systemic models to provide a superior analysis of the system's behaviour, generating insights on efficient strategies to control exposure. Examples from the results presented in this thesis are:

- Results in Chapter 4 identify stages of disposal common to a range of disposal options. Policy intervention that address this stages of disposal, achieve in reducing the overall risk of exposure to hazardous agents to all disposal option sharing that stage.

- Results presented in Chapter 10 address the concept of low probability events (LPE) and their contribution the exposure of UK livestock to an EAD. Figure 10.1 displays an analysis of pathways lengths based on their influence on system behaviour. Here pathways of introduction were separated into simple introduction scenario (SIS - these are the pathways conventionally assessed in scenario based models) and complex introduction scenarios (CIS – these represent the LPE available in the system - Section 10.3). The results describe that the likelihood of introduction through any one CIS it greater than introduction through any one SIS, thus suggesting the need to improve control over CIS. However, these represent more than 99% of the pathways of exposure available in the system, thus making policy interventions addressing each CSI individually inefficient. Here, systemic models provide further insight on system behaviour. The framework recognises that process/events are common to multiple pathways of exposure. Therefore, interventions targeting process/events with a significant influence in exposure to EAD, the identified CCP, will reduce exposure through SIS and CIS simultaneously (Section 10.4).

Systemic models focus on improving the available insight on system behaviour. This characteristic of systemic models allows them to inform on efficient strategies to improve control over the system's behaviour and reduce likelihood of exposure. The model applications presented here improve the understanding of the behaviour of the systems associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases, generating, for each phase, insights on efficient approaches to intervene in the system.

11.2.4 Improving the quantity and quality of data to support policy interventions

The analysis of the results presented reveals that systemic models develop analyses of the system that consider all pathways of exposure; produce unbiased comparison of pathways of exposure and process/events based on their influence on system behaviour and; provide an understanding of system behaviour that generates insights on efficient intervention strategies. This research, taken together (Chapters 4, 5, 8, 9 and 10), presents the first application of systemic models to study EAD transmission during the pre-outbreak and post-outbreak phases. The systemic models improved the information and insights developed by the prior art and succeeded in providing insights over the research opportunities identified in the literature (Section 2.6). Thus, expanding the quantity and improving the quality of information available to support policy developments to reduce UK's vulnerability to EAD (Section 2.7). The significance of this work is: analyses developed through the application of systemic models provide insight on how to intervene in the system and, through the identification of CCP, on where to intervene in the system. This information, made available to policy makers, allows priorities to be set and policy intervention to be developed better.

11.3 3-tier format for communicating outputs

In this section, I critique the communication of the outputs produced to support policy development, in light of the research presented in Chapter 4, 5, 8 and 9. Risk assessments have a longstanding relation with the development of policy interventions (Section 2.1.3). Thus, risk analysts and policy makers have a vested interest in being presented with the most complete data to set priorities and support informed policy decisions. The prior art demonstrates conventional risk assessment models associated with one-dimensional formats to communicate the outputs (Section 2.2 and 2.3). These are nominal scales for expert based models (Section 2.2.1 and 2.3.2) and numerical values of likelihood or quantity of EAD agent released for scenario based models (Sections 2.2.3 and 2.3.1). These formats reduce the output to a value and fail to integrate the significance of the findings onto the system's behaviour. The methodological limitations of conventional risk assessments (Sections 2.4 and 11.2) alongside the format selected for communicating the output, results in a failure to provide 1) an image of the entire system, i.e. describing all pathways of exposure available in the system, and 2) fail to establish a relation between the priorities identified and their influence on system behaviour. In short, conventional risk assessment models develop and communicate outputs that are limited in their capacity to inform policy interventions aiming to improve significantly system behaviour.

This research states, systemic models overcome the methodological limitation presented by conventional risk assessment (Section 11.2). Here, we present an improved format to communicate the outputs of systemic models, ensuring the full extent of the findings is communicated to risk analysts and policy makers (Sections 4.3.1, 5.3.1 and 8.4.2). These insights, now available allow priorities to be set and support the development of informed policy decision. The format for communication of the outputs is based on three tiers, thus providing an analysis of the system at three levels of detail.

The first tier is a high-level analysis, which displays an overview of the drivers of exposure considered by the system. Examples from the research presented here are:

- The first tier analysis for the post-outbreak phase is presented in Figure 4.3, comprising a Pareto assessment of all stages of disposal considered in the system. The Pareto principle is applied to identify the stages of disposal with greatest influence on system behaviour (Section 4.3.1, (Delgado et al., 2010)).

- The first tier analysis for pre-outbreak phase is presented in Figures 8.4 and 9.3, presenting an analysis of the network nodes, identifying those posing a greatest influence in system behaviour.

Thus, the first tier communicates overall system behaviour and identifies the most vulnerable aspects of the systems' structures (Sections 8.4.1 and 9.3.2).

The second tier identifies specific activities and pathways of exposure responsible for generating the high-level risk. Examples from the research presented here are:

- The second tier analysis for post-outbreak phase is presented in Figure 4.4 and Figure 4.5, comprising a Pareto analysis of the pathways of exposure associated with the disposal stages and identifying the pathways driving exposure within each stage (Section 4.3.1).
- The second tier analysis for the pre-outbreak phase is presented in Figures 8.5 and Figure 9.4, providing an analysis of the process/events responsible for inter-node connectivity for a specific node (in this case human population). This analysis identifies the process/event with a higher influence in system behaviour (Sections 8.4.1and 9.3.2).

The second tier analysis identifies the systems' CCP, providing insights on specific pathways and activities responsible for the vulnerabilities of the system. Here, intervention is likely to improve significantly system behaviour (Delgado et al. 2010).

The third tier describes additional descriptive information on the failure causes responsible for exposure. Examples from the research presented here are:

- The third tier analysis for the post-outbreak phase identifies the hazardous agents released at the end of each pathway, following the disposal of carcasses (Table 5.2 and Table 5.3).
- The third tier analysis for the pre-outbreak phase identifies the causes for failing to detect and eliminate an EAD prior to the exposure of UK livestock. For example, for the arc representing movements between countries outside the EU and the domestic residences, the third tier states *"risk targeted enforcement was unable to check all passengers and packages and there was a lack of awareness amongst travellers"* (Section 8.4.1).

The third tier provides context to the events driving exposure. This information has a twofold function. Firstly, it provides access to the rationale used by experts to perform the assessment. Secondly, it provides context to the values provided by the assessment, allowing decision makers to develop risk mitigation solutions that target specific causes of failure and specific hazardous agents released into the environment. Henceforth, it contributes to the increase in efficiency of future intervention strategies that spawn from these assessments.

The 3-tiered approach to communicating the output format presents, through a sequence of perspectives the complete image of source-pathway-receptor relationships. This format partitions the output into smaller size units. The results presented (Sections 5.3, 8.3 and 9.3.2) follow a sequential increase in detail that allows decision makers to move from a general overview of the system towards a detailed analysis of individual pathways or events driving exposure (Delgado et al., 2010), ending with the description of the causes of barrier failure or hazards exposed.

This research, taken together, offers a 3-tier approach to communicate the systemic analysis of EAD risk. For the first time, risk analysts and policy makers can now see the full extent of the system, from individual components to system structure, thus allowing priorities to be set and intervention to be devised better.

11.4 Maximising expert opinion

In this section, I critique the improvements to the application of expert opinion in systemic models, based on the research presented in Chapters 4, 5, 6, 7. Expert opinion is used frequently in the prior art, in models used to study the pre-outbreak and post-outbreak phases of EAD outbreaks (Sections 2.2.1, 2.2.2 and 2.3.2). Models using expert opinion rely on experts to provide information and to produce the outputs (Taylor, 2003).

The research literature is vague, but suggests the elicitation process focuses on promoting group discussion on commodities imported and classification according to a nominal scale (Defra, 2011c; DH, 2001; BioNZ, 2006). There are exceptions in the prior art (Section 2.2.2), however, these are the minority (Horst et al., 1998; Horst et al., 1996; Nissen and Krieter, 2003; Gallagher et al., 2002). The criteria for selecting experts targets high-level officials and animal health specialist, producing expert panels with a general understanding of the system (Defra, 2011c; DH, 2001; BioNZ, 2006). The combination of elicitation process and criteria for expert selection, results in the superficial analyses of the system that is characteristic of expert based qualitative assessments (Taylor, 2003, Peeler et al., 2006). All expert based assessments available in the prior art, for the pre-outbreak and post-outbreak phase fail to assess specific pathways of exposure (Sections 2.2 and 2.3). Thus, such models produce outputs that provide limited insights on system vulnerabilities and contribute little to expand the existing understanding of system behaviour.

Here, we have advanced the use of expert elicitation as a source of information by developing models combining the use of expert opinion and computer modelling. This resulted in the development of models that do not rely on the experts' rationale to produce the output. This changes the role of experts in the models and with it the criteria used for expert selection (Chapter 7), allowing improvement in the quality of the expertise selected to provide input (Cooke, 1994; Cooke and Goossens, 2000). The research, presented chronologically, describes a progressive transition from the conventional use of expertise (Chapter 4) to a more efficient use of expert opinion (Chapter 6 and 7).

The research presented in Chapter 4 explores the potential of the modelling approach published by Pollard et al. (2008) to develop a systemic analysis of carcass disposal activities (Delgado et al, 2010). This model applies a framework that represents the entire system's structure to ensure experts assess all pathways of exposure. It introduces a description of the system that guides experts to providing a comprehensive analysis of the pathways of exposure. The model uses expertise from high-level officials and relies exclusively on the experts' rationale to assess risk of exposure presented by the pathways (Figure 4.2 and Table 4.2). Although a conventional panel of experts is used to inform and produce the outputs, the combined use of expert opinion and system representation, resulted in an analysis of the entire system with a level of detail (Figure 4.4 and Figure 4.5) that was previous unavailable in the prior art (Section 2.3.2 and 2.3.3).

The research presented in Chapter 5 builds upon the combination of a framework and expert opinion (developed further in Chapters 6 and 7) to improve the use of the expertise available. Here, the research presents a modelling approach that combines the use of expert data and computer models. The framework representing the system is associated with a computer model that is responsible for generating the pathways and estimate exposure (Sections 5.2.3 and 6.3). Experts provide the input data for the model but are not responsible for providing the output (Sections 5.2.4 and 6.2.2). This application of expert opinion changes the role of the experts and with it the parameters for expert selection (Section 5.2.4, &.7.2.2).

The research presented in Chapters 6 and 7 takes full advantage of this characteristic. The model relies on experts to inform on the causes and frequency of failures of the barriers within the system. A computer model integrates these data and generates insight on system behaviour. This allows for selecting as experts, individuals that do not have an understanding of the entire system. Thus, it expands the pool of available experts to consider those individuals with a narrow but insightful expertise on specific barriers to EAD transmission (Table 7.1). As a result, the model collects information on barrier failure, form individuals that have the responsibility to enforce them, suggesting a privilege insight on their performance and failure causes. This is defined a "practitioner's expertise" in Chapter 7, and suggests these models are based on the most accurate and up to date information (Chapter 8 and 9).

The research presented here presents an alternative use of expert opinion applied to the study of EAD. For the first time, the expertise sought after is not that of high-level officials and animal health specialists, and instead focuses on those individuals with a narrow but insightful expertise resulting from the daily tasks they perform (Table 7.1).

The computer models integrate the insights from a large number of experts with "practitioner's" expertise, thus allowing the development of insights on system behaviour, supported by expertise on specific system components (Section 6.2). As a result, the research presented in Chapter 8 and 9 uses information from experts in privilege positions to assess the efficacy of the controls in place, thus maximising the use of information currently available to perform the assessment (Cooke, 1994; Cooke and Goossens, 2000). Outputs produced through this approach are based on the most accurate and up to date information. Thus, allowing better informed priorities to be set and policy interventions to be defined better.

11.5 <u>Comparison of models</u>

In this section, I critique the role of systemic models based on the research presented in Chapter 4, 8, 9 and 10. This section focuses on identifying the roles of systemic models to support policy development for EAD, considering the range of tools available in the prior art. The models used in the prior art were not originally developed to infer on a systems behaviour (Section 2.4). Their use for such a purpose resulted in a misapplication of the models. For example using a combination of expert based and scenario based models to infer on system behaviour (Section 2.5) or the development of comprehensive scenarios based models, which infer on system behaviour based on an incomplete analysis of the system (De Vos et al., 2004). The introduction of systemic models is followed by the need to redefine the role of the models now available, to ensure their correct application within their modelling capabilities. From the analysis of the models in the prior art we conclude that:

Expert-based models develop scanning exercises considering the entire system, but without specifying or considering pathways of exposure in any level of detail (Defra, 2011c; BioNZ, 2006). Thus, expert based models allow developing analyses of the system in the short-term, but producing limited information on ways to improve the detected vulnerabilities (Sections 2.2.1 and 2.3.2). The prior art associates expert based models with emergencies, where the need to act, presses the time available to produce the assessment (Defra, 2011c; DH, 2001).

Scenario based models analyse specific pathways of exposure with a great level of detail (Sections 2.2.3 and 2.3.1). Here data is collected and applied to inform on all barriers to transmission from source to receptor, making these models time and resource consuming (Vose, 2008; Murray, 2002). This constrains the number of pathways assessed to one or a small number of them, thus scenario based models fail produce analyses of the entire system (Taylor, 2003; Morley, 1993; Yu et al., 1997; Martinez-Lopez et al., 2008; Hoar et al., 2004; Jones et al., 2004; Astudillo et al., 1997; Weng et al., 2010). The prior art associates these models with "times of peace" and applied to understand past events, to generate insights to prevent future incursions through these same pathways.

Here, systemic models expand the range of risk assessments models applied to study the pre-outbreak and post-outbreak phases. Systemic models focus on developing analysis of the entire system and assessing its pathways (all of them) to inform on system behaviour (Section 4.3, 8.3 and 9.3). These models strike a middle ground between expert based and scenario based models regarding the level of detail with which pathways are assessed and the time necessary to develop analyses (Figure, 4.4, Figure 4.5, Figure 8.5 and Figure 9.3) . However, they produce superior insights on system behaviour and on opportunities to improve UK's resilience to future EAD outbreaks (Section 0).

Based on this review, we suggest using: 1) expert based models to identify vulnerabilities in the system, during emergencies; 2) systemic models to produce a more detailed analysis of the system, of its behaviour and vulnerabilities, when time is available and; 3) scenario based models to explore further the vulnerabilities identified by systemic models and to study past events identified in research literature and epidemiological reports.

For the first time, risk analysis and policy makers have at their disposal a range of modelling approaches to analyse vulnerabilities in systems associated with EAD transmission. The systemic models presented here, do not replace the methods available in the prior art. Instead, by expanding the list of models available, we ensure model application is confined to its capacity, thus avoiding the misapplication of models that compromise the quality of the insights generated. Using these models correctly supports the development of high quality outputs, ensuring that policy interventions are supported by accurate and relevant data.

11.6 Comparison with disease spread models

In this section, I critique the use of systemic models in light of the research presented here (Chapter 4, 8 and 9) and the current use of disease spread models (Section 2.1.4). The prior art describes similarities in the approach used to develop disease spread models and our advanced approach to develop systemic models (Section 2.1.4). In theory, the application of disease spread models can focus on assessing the inter-farm movements, to detect vulnerabilities and opportunities to improve the controls in place to prevent exposure (Kitching et al., 2005; Harvey et al., 2007; Garner and Beckett, 2005). However, in current applications these models focus on producing a different analysis of the system. These analyses are based on the development of a base case for disease spread, followed by an assessment of the effects different policy interventions have on the spread and exposure to EAD (Kitching et al., 2006; Kobayashi et al., 2007). Thus, such application of disease spread models allow for considering the economic and social aspects of disease intervention.

The similarities in approaches for model development (Section 2.1.4) suggest that systemic models are able to analyse the effects that changes to the system, planned and unplanned, have in UK's vulnerability an EAD. This includes using systemic models to test scenarios of exposure that consider factors exterior to animal health policies. For example, the effect of the current budget cuts in the resilience against an EAD outbreak (Alistair, 2010; BBC News, 2010). This use of systemic models produces information to support decisions to increase the effectiveness of the available protections measures and/or reduce their cost (Kitching et al., 2006; Kobayashi et al., 2007). Thus, it informs on system behaviour in manner that focuses on developing strategies to produce cost-effective solutions and thus optimising protection against an EAD outbreak.

The potential for such an application suggest that in the research presented in the Chapters 4, 8 and 9, system models do not achieve their full potential. Testing such an application of systemic models can provide an interesting challenge for the future. If possible then for the first time, risk analysts and policy makers have at their disposal a modelling technique that allows testing policy interventions considering the limits of the available resources. Future applications of the systemic models can assess the cost and benefits of policy interventions, supporting the development of more informed policy decisions.

11.7 Modelling with limited data

In this section, I critique the sources of uncertainty associated with the systemic models presented in this thesis based on the methods described in Chapter 4 and 6. Specifically, uncertainty associated with the limitations of the data available in the research literature and expert opinion. The results presented in this thesis do not provide an estimation of the level of uncertainty (Section 4.3 and 8.4.3). However, systemic models are sensitive to the limitation of data available in the research literature on the events taking place during the pre-outbreak and post-outbreak phases (Section 2.1.3), and the influence of biases in expert opinion is documented (Cooke, 1994; Tversky and Kahneman, 2000). Therefore, uncertainty is likely to be present in the results. Addressing the uncertainty is central to improve the systemic models capacity to provide an output that is coherent with the events occurring during the two phases of an EAD outbreak. Thus, it improves the quality of the information available for the development of policy interventions. Here focus is on the uncertainty associated with the elicitation exercises (Chapter 7) and with the information available in research literature to develop representations of the systems (Section 2.1.3).

11.7.1 Uncertainty from expert opinion

Risk assessments based on expert knowledge depend on the expert's capacity to develop accurate expert judgements. Expert elicitation exercises are dominated by the adequacy of the ranking scale to capture the magnitude of the event (Cobb, 1998; Cox and Babayev, 2005), by the heuristics associated with expert biases (Cooke, 1994;

Tversky and Kahneman, 2000) and by the experts understanding of the assessed events (Jousselme et al., 2003; Lipshitz and Strauss, 1997). The prior art, associated with EAD and with the wider field of risk assessments is vague in suggestions for the development of elicitation exercises (Neale, 1988; Ford and Stermanb, 1998). The elicitation method used was influence by this lack of guidance and as expert opinion is the sole source of input data, the elicitation exercises are the subject of great concern.

Drawing upon large quantities of elicited data required elicitation protocols that considered the limitations in resources regarding time, cost and expert availability (Chapter 7). Our approach focussed on *simplicity*, easiness with which participants understand the task and the nature of the materials provided for the exercise (Hoffman et al., 1995), and *efficiency*, the rapid generation of information (Hoffman et al., 1995). However, this constricted the capacity to confirm *validity,* i.e. exercises to confirm the accuracy of the data collected (Hoffman et al., 1995). Specifically, the elicitation protocol uses expert consensus to generate the variables, however the verification exercises were performed post elicitation.

Limitations in time and expert availability excluded the use of more robust elicitation techniques and to include data verification exercises as integrative part of the elicitation protocol (Section 7.2). Ignorance prevails regarding the quality and accuracy of the data produced. Considering the volume of information to elicit, alongside the limitations in time and expert availability, the elicitation protocol selected fits the needs of the model (Section 7.2). However, it is advisable that future applications of the model revise and test its true potential and if need, improve or replace the elicitation exercises currently proposed.

11.7.2 Information available on the source-pathway-receptor relationship

Developing a representation of the system involves drawing upon information, available in the research literature and as expert opinion, to inform on the system, the system components and on the pathways of exposure. However, information on past EAD outbreaks is limited (Section 2.1.2), thus challenging the level of insights available to define accurately the systems and system components. Specifically, it influences the capacity to identify all pathways of exposure. Here, a poor characterisation of the system influences the pathways assessed by the systemic models and may result in an application of the model that does not assess all available pathways of exposure. Examples of the effect of prior knowledge in system development are:

- The systemic model for the post-outbreak phase (Chapter 4 and 5) uses prior knowledge to define the disposal options, the stages of disposal considered for each option and the suit of pathways of exposure considered from each stage of disposal (Table 4.2). Specifically, the model application assumed there is a sound understanding of the environmental fate of hazards and disposal activities (Section 4.2). Thus, that it is possible to identify all pathways of exposure. If this assumption is correct, the model represents a truly systemic analysis of exposure to hazardous agents. However, if the assumption is incorrect, it may have resulted in the exclusion of those pathways of exposure that are unknown. Thus, this systemic model is vulnerable to the limitations of information on past EAD outbreaks and the environmental fate of hazards.
- The systemic models for the pre-outbreak phase (Chapter 8 and 9) acknowledge that the large number of pathways of exposure available for introduction of an EAD (Section 1.3.1) alongside the limited information on past outbreaks

(Section 2.1.2), challenges the capacity to define all pathways of exposure. Thus, the model adopted an approach where it is a computer model that generates the pathways of exposure (Pearce and Merletti, 2006; Dangerfield and Morris, 1992; Freeze et al., 2005). The computer model draws on the information produced by the elicitation process and generates all pathways of exposure available in the network (Section 6.3). However, the elicitation process depends on the prior identification of the system's features (network nodes) during the first elicitation phase (Section 7.2.1). The systemic models used information from the research literature and expert opinion to define the system and network nodes. Here, a poor definition of the system, which excludes a network node results in the exclusion of all pathways associated with it. Thus, the systemic model is vulnerable to the limitations of information on past EAD outbreaks.

The level of insight available on the system's behaviour generated from analyses of past outbreak influences the development of the systemic models to EAD. Here, limited information jeopardises the comprehensiveness of the system, compromising systemic models from developing a truly systemic analysis of the system.

The development of a representation of the system represents a key stage of the development of a systemic model (Murthy and Krishnamurthy, 2009; Freeze et al., 2005; Zio, 2009). Thus, the use of prior knowledge, as data available from the research literature and as expert knowledge, to develop system representations poses concern. Model development, specifically the systemic model for the pre-outbreak phase (Sections 7.2.1), dedicates significant resources to ensure the framework (network nodes) representing the system is accurate. However, it is advisable that future applications of the model revise the use of prior knowledge and improve or replace exercises currently proposed.

11.7.3 Overcoming data limitations in future applications

The research presented in this thesis represents a first application of systemic models to develop analysis of EAD outbreaks, specifically for the pre-outbreak and post-outbreak phases (Chapter 4, 5, 8 and 9). These models address systems for which limited information is currently available to inform on system behaviour, pathways of exposure and vulnerabilities (Section 2.1.2). The development and application of systemic models to study EAD transmission improved the quantity and quality of the information available to support policy interventions. However, the development of a novel tool for assessing risk carries with it methodological challenges that need overcoming to improve the robustness of the output produced.

Systemic models adopt modelling solutions from other areas of risk assessment, where developments are still necessary. Namely the application of systemic models to open systems and epidemiologic studies (Pearce, 1996; Pearce and Merletti, 2006; Mitchell, 2006; Boccara, 2004) and the management of uncertainty associated with expert elicitation (Cooke, 1994; Tversky and Kahneman, 1974; Cooke, 1991; Slottje et al., 2008). It is safe to assume that progress in these areas will advance the methodological solutions available to build systemic models, making future applications to the study EAD transmission more accessible.

The methods used to gather expert opinion currently represent a likely source of uncertainty for the models' outputs. Expert opinion allowed overcoming some of the limitations of the records from past outbreaks (Section 2.1.2), providing the opportunity to develop the systemic analyses of the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases of an EAD outbreak. However, the scarcity of information on source-pathway-receptor relationships influences the accuracy of the outputs. The limitation of the available data affects the development and identification of the pathways, and may have resulted in the exclusion of those pathways of exposure unknown to experts. Besides this, data scarcity challenges and limits the possibilities for model validation through external validation (sections 4.3 and 8.4.3) (Wooldridge et al., 2006). This is the validation of the output through comparison with historical data, collected from previous outbreaks, epidemiological studies and risk assessments (Sargent, 2007; O'Keefe et al., 1987).

Defining the pathways and validation were predictable challenges (Murthy and Krishnamurthy, 2009; Freeze et al., 2005; Wooldridge et al., 2006; O'Keefe et al., 1987). Thus, model development ensured periodic verification exercises, using an expert panel to ensure the modelling approaches are valid and fit for purpose and allows to expert validation of the output (Sargent, 2007; O'Keefe et al., 1987). Despite the solutions adopted to minimise the negative influence of data scarcity, uncertainty is likely to be present in the outputs produced. Future applications of systemic models to EAD must address the use of data from research literature and expert opinion to ensure accuracy in the outputs produced.

11.8 Improving policy development associated with EAD outbreaks

This work defends a superiority of systemic model to produce information that supports decisions that aim to optimise the level of protection against an EAD outbreak. This assumption is based on the use of systemic model to study disease spread and in other areas of risk assessment. The strength of these models results from *(i)* establishing a relation of cause and effect between the factors influencing EAD transmission and system behaviour, and *(ii)* generating insight on all factors posing an influence regardless of likelihood and impact. As a result, systemic models develop a comprehensive analysis of the systems associated with the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases of an EAD outbreak, resulting in the identification of high-level priorities and CCP and detection of trends leading to EAD exposure, such as the low probability events (LPE). These insights on system behaviour expose system vulnerabilities and provide insight on efficient approaches to minimising exposure, the extent to which is beyond the reach of the predictive models previously applied to study these phases of EAD outbreaks. As a result, these models help overcome some of the information limitations identified in literature, regarding opportunities for controlling the EAD transmission and exposure and thus strengthening the available information to support decision across all phase of an outbreak.

Expert-based systemic models represent a development of the tools available to support decision-making during the pre-outbreak (pre t_0) and post-outbreak (post t_2) phases of an EAD outbreak. These models produce an analysis of the pathways system that is consistent with that of disease spread models, reducing the inequality in available information to perform decisions between the these two outbreak phases and the outbreak (t_0 t_2) phase. Such models improve the decision-making capacity across all stages of an EAD outbreak, nonetheless they do not achieve in producing information of similar quality to that available to support decision in the $t_{0\text{-}2}$ phase. Increasing the quality of information produced involves development of modelling techniques that address the concerns identified in model application. Most importantly is must include improving the source of available information in the research literature, particular by producing a more accurate recount of the events occurring during EAD outbreak (documentation of past outbreaks). Only the conjoint effort to improve these two information sources can improve the existing understanding of system behaviour. Despite this, in light of the insights produced by the systemic models, alongside the current use of systemic models in other areas (Murthy and Krishnamurthy, 2009; Freeze et al., 2005; Zio, 2009), systemic analyses present advantages to policy development. Thus, it is logical to assume that these models are likely to be involved in the future on EAD management.

The development of these tools for EAD suggests their wider application in other areas is also possible. Systemic models are likely to prove useful at a time where threats are not always foreseeable and in a society evermore risk conscientious as demonstrated by the position adopted by the British government (Risk Support Team: HM Treasury, 2004).

12 CONCLUSIONS

The research in this thesis, **presents the first application of systemic models to study EAD outbreaks**. Specifically, to study two critical phases of an EAD outbreak for which information is to support policy interventions is limited (Section 2.1.3), the pre-outbreak and post-outbreak phases. **We have expanded the modelling solutions available in the prior art to consider systemic models,** and in light of the results presented in Chapters 4, 5, 8, 9 and 10 with benefits to the insights available on exposure to support policy development for these two outbreak phases. **For the first time, risk analysis and policy makers have at their disposal models that produce analysis of the entire system, from system component to system structure**. The results suggest **systemic models are superior in the capacity to understand the system's behaviour and identify its vulnerabilities thus, allowing priorities to be set more accurately and policy interventions to be defined better.** Insights and claims of novelty in this thesis are associated with the insights developed for the two outbreak phases and the characteristic of systemic models that are of benefit to policy development. Based on the research and results presented we conclude the following:

1. The application of systemic models to study the post-outbreak phase brings an **improved level of understanding on exposure across the process chain associated with the disposal options** (Chapter 4 and 5). The systemic model (Chapters 4 and 5) produces **the first comprehensive analysis of exposure to hazardous agents from disposal activities, considering all disposal options, disposal stages and pathways of exposure.** Furthermore, we believe this to be **the first application of Pareto analysis** to generalized policy-level exposure

assessments (Section 4.3.1). This research **provides evidence base that allows for the first time** to:

- Highlight the large number of high-risk pathways during the initial phases of carcass disposal and during the collection and loading of carcasses on farm (Figures 4.3, 4.4 and 4.5) that present a significant influence in exposure to hazardous agents.
- Set priorities for policy interventions based on a comprehensive analysis of all pathways of exposure and carcass disposal activities influencing system behaviour.

Without the development and application of a systemic model, it would have been difficult to state, with any authority, the vulnerabilities of the existing controls (Delgado et al., 2010), allowing policy officials to direct risk management efforts accordingly and communicate a rationale for intervention priorities.

2. The application of systemic models to study the pre-outbreak phase brings an **improved level of understanding on the on causes of failure of the multi-barrier system associated with preventing introduction and exposure of EAD to livestock (Chapters 8, 9 and 10)**. The systemic models produced **the first comprehensive analyses of exposure to EAD, considering all system components and their interactions and the multi-barrier systems of controls to prevent exposure of livestock to EAD.** We believe this to be **the first application of a model built from the bottom-up to** support a generalised policy level exposure assessment (Chapter 6), associated with the introduction of

CSF and FMD. This research **provides an evidence base that allows for the first time** to:

- Identify the influence of the role played by the human population, domestic animals/backyard farms and animal gatherings in enabling introduction and exposure of EAD (Figures 8.4 and Figure 9.3).
- Highlight the influence of low probability events in undermining the UK's resilience to EADs and determine the best approach to control them (Chapter 10).
- Set priorities for policy interventions based on a comprehensive analysis of all process/events influencing system behaviour.

Without the development and application of systemic models, it would have been difficult to state, with any authority, the vulnerabilities in the existing controls, allowing policy officials to direct risk management efforts accordingly and communicate a rationale for intervention priorities.

3. Models developed according to the systemic principles support the development of systemic models that produce comprehensive analysis of the systems, improving the level of understanding on the system's vulnerabilities and behaviour (Section 11.8), exemplified in the research presented in Chapters 4, 8, 9. These principles are:

- **establish a relation of cause and effect between the factors influencing EAD transmission and system behaviour, and**
- **generate insight on all factors posing an influence regardless of likelihood and impact.**

The systemic models presented here **expanded the number of pathways** assessed for the pre-outbreak and post-outbreak phases (11.2.1), improved the quality of the output by **minimising the effects of expert biases and prejudice** on the outputs (11.2.2) and; developed **insights in system behaviour** that allowed to detect efficient ways to control exposure (11.2.3). As a result, the output produced allowed to:

- **Identify vulnerabilities overlooked** by models in the prior art (Sections 4.3, 10.1 and 11.2.2),
- Identify **patters of system behaviour that allowed developing more efficient policy intervention** (Section 10.3.3 and 11.2.3).

Considering the limitations in the prior art (Section 2.1.2), **models developed according to the systemic principle (systemic models) are an essential tool to develop insights that allow priorities to be set and policy intervention to be defined better.**

4. This research improved the format used for communicating the results. This improved on one-dimensional methods of communicating risk present in the prior art (e.g. nominal scales and numerical outputs), to providing a 3-tier approach to communicating the outputs (Section 11.3). **For the first time, policy maker and risk analysts can see the full extent of the system, from system structure to individual components**. This format allows to:

   - **Identify vulnerabilities in the system structure** (Figure 4.3, 8.4 and 9.3);

- **Recognise the system's critical control points (CCP)** (4.4, 4.5, 8.5 and 9.4), were intervention is likely to improve significantly protection against EAD (Chapter 4) and
- **Provide insights on causes for system failure,** to support the development of efficient policy intervention (Tables 5.2 and 5,3 and Section 8.4.2).

The 3-tier format allows, **for the first time to communicate the full extent of the outputs, now available, to risk analysis and policy makers, from system components to system structure** (Sections 5.3, 8.3 and 9.3). Thus, priorities can be set with confidence, and policy interventions defined better.

5. The research presented advanced the use of expert opinion in study of EAD. We believe these are **the first models applied to study the transmission of EAD to combine expert opinion with computer models (Chapter 6)**. Here, experts provide the input data but not the outputs of the models (Section 8.2.2 and 9.2.3), changing their role from that performed by experts in models available in the prior art (Sections 2.2.1, 2.2.2 and 2.3.2). This allows changing the expert selection criteria. T**he systemic models developed to study the pre-outbreak phase (Chapter 8 and 9) selects:**

   - **Experts with a narrow but insightful expertise on specific system components considered in the network.**

   Expertise selected through this criteria is defined as **"practitioner's" expertise** (Section 7.2.2) and targets experts that:

   - **Have privilege insights on barrier efficiency and failure causes, based on the most accurate and up to date information**.

This research, **offers for the first time** risk assessment models that develop insights on system behaviour supported by individuals with expertise on specific system components (Table 7.1). **Models using these criteria for expert selection (practitioner's expertise) provide the most accurate insights on system behaviour and vulnerabilities (Section 11.4)**.

6. The research presented in this thesis is based on the development of novel methodologies to develop comprehensive analysis of EAD transmission. The research recognises **that long-term commitments to improve records of EAD outbreaks and modelling approaches are necessary to improve insight on the EAD transmission during the pre-outbreak and post-outbreak phase**. Progress in that direction must include an analysis of the potential uses of systemic models and identify methodological vulnerabilities for consideration in future applications. Here I present the following suggestions for **future work**:

    - **Apply systemic models to study the effects of policy changes and to analyse the cost and benefits of policy interventions** (Section 11.6);
    - **Revise the use of prior knowledge and expert opinion in the systemic models for the development of more robust models** (Section 11.7.1 and 11.7.2) and;
    - **Improve systemic models according to the novel insights on the study of open systems and epidemiological studies** (11.7.3).

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15 ANNEX 1

Outputs of the first stage of elicitation develop for the Import risk assessment of Classic Swine Fever. This activities developed in this stage provide a definition of the network nodes.

15.1 Network nodes for Classic Swine Fever

15.1.1 Node definitions

Outside EU [Source] All Countries outside the European Union, including third world countries, trading partners and bilateral [independent of absence/presence of CSF].

EU [Positive] [Source] All EU member countries where the disease is present, currently without disease free status [Independent of the affected area, e.g. nationally or regionally].

Laboratories [Source] Laboratory facilities that might handle CSF contaminated material.

EU [negative] All EU member countries benefiting from the European free market agreement, currently under the disease free status [including potentially false negative countries].

Border Inspection Post All Border Inspections posts [independent of location airport or nautical port].

Environment Potential fomites [grazing fields, water-bodies...], all flora and all fauna not included in the list of receptors.

Wildlife [wild boar] Wildlife populations susceptible to the disease present within English territory.

Petting zoo /Pet shop includes Zoos [urban and rural] including petting zoos and pet shops.

Food markets/Retailers/Restaurants/Caterer Entities responsible for making food goods available to the general public, including supermarket, local market, butchers and restaurants and caterers

Feed factory All facilities producing feed; feed additives; supplements; and other products to be used in livestock feeding

Domestic residence The location of residence and movement for the human population: including British Citizens, immigrant communities and migrant work forces

Veterinarian./fieldsmen/other intervenient The personnel involved in the farms routine activities that might play a part in disease transmission performing movement [Veterinary personnel; fieldsman; and other personnel in the position of acting as a fomite]. Does not include commuting movements between domestic residence and farm

Slaughterhouse/meat processing plants All slaughter houses and all plants involved in the transformation of meat products

Livestock vehicles Any vehicles involved in the transport of live animals. It represents the vehicle as a fomite, where the contaminated material within the vehicle, contaminates a group of disease free animals, environment...

Domestic animals/ Backyard Farms Livestock not bred for slaughter and small livestock aggregates, includes pet pigs, hobbyists and backyard farmers

Waste disposal Waste disposal facilities capable with dealing with potentially CSF contaminated waste.

Animal gathering [Receptor] National and international animal gathering events within English territory (animal shows, markets), these are associated with gathering of animals from multiple proveniences.

Farm [Breeding units] [Receptor] All breeding company breeding herds (nucleus and multiplier); weaner breed herds; and breeding finishing units It is usually associated with intensive production systems and characterised by a high bio-safety level.

Outdoor Finishers [Receptor] All weaning and finishing outdoor units

Indoor Finishers [Receptor] All in-housing finishing units; and breeding companies grow out units

Figure 15.1 Collection of nodes develop in the first stage of elicitation applied to studying the introduction of CSF into England (Chapter 8)

[KEY] Blue nodes represent potential disease sources; red nodes represent receptors, simulation stops when CSF reaches these nodes, green nodes represent full functioning nodes, providing a connection between source and receptors.

16 ANNEX 2

16.1 Classic Swine Fever FEP LIST

Table 16.1 Outside EU

Receptor node	Flow rate	Minimum	Maximum	Comments
Domestic residence	1.E+05	1.E-01	1.E-02	Personnel imports are regulated however risk targeted enforcement unable to check all lack of awareness amongst travellers
Petting zoo/pet shop	1.E+02	1.E-05	1.E-07	Measures are in place to control animal imports
Veterinarian./fieldsmen / other intervenient	1.E+03	1.E-04	1.E-05	No comments recorded
Waste disposal plant	1.E+05	1.E-05	1.E-06	Controls are on international catering waste, licensed and controlled - relies on cooperation between carriers and delivery agents involved
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-03	1.E-04	Little evidence suggests direct contact to restaurants, although unknown (barriers are the BIPs, Border controls, Licensing catering permits
Feed factory	1.E+02	1.E-06	1.E-07	Licensing of feed factories is highly controlled
Domestic animal/ backyard farms	1.E+04	1.E-01	1.E-02	No comments recorded
Environment	1.E+03	1.E-02	1.E-04	Direct connections to the environment are unlikely
Wildlife	1.E+02	1.E-04	1.E-06	Only possible if feed is illegally imported a fed to wild boars
Animal gathering	1.E+02	1.E-06	1.E-07	Negligible imports
Farms Breeders	0.E+00	0.E+00	0.E+00	No live animal (Pigs) imported from outside the EU

Outdoor Finishers	NA	NA	NA	No live animal (Pigs) imported from outside the EU
Indoor Finishers	NA	NA	NA	No live animal (Pigs) imported from outside the EU

Table 16.2 EU [Positive]

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]				
EU [negative]	1.E+04	1.E-01	1.E-02	Personal imports are the greatest concern. Barriers involve legislation and certification, and are more effective for commercial transactions
Border Inspection Post	NA	NA	NA	Not applicable
Laboratories	1.E+02	1.E-05	1.E-07	*Values not used for simulation 1) Variation of barrier efficiency recognised routes vs. unknown Note: Recognise efficacy of BIP for product coming in through recognised, less likely routes are of higher risk
Slaughterhouse /meat processing plants	1.E+02	1.E-05	1.E-06	Certification should effectively stop movement
Livestock Vehicles	1.E+03	1.E-04	1.E-05	Livestock vehicles may come back from a diseased area. Cleaning & Disinfection is the main protective barrier
Domestic residence	1.E+04	1.E-02	1.E-03	Personal imports (Illegal) of meat products
Petting zoo/pet shop	1.E+02	1.E-06	1.E-07	Visitors to Zoos and Pet shops
Veterinarian./fieldsmen / other intervenient	1.E+02	1.E-05	1.E-06	Veterinarians pose minimal risk. Fieldsman higher risk may visit a farm in a diseased area
Waste disposal plant	1.E+02	1.E-06	1.E-07	Highly regulated - Unlikely for waste to come from elsewhere in the EU from processing main risk is international catering waste
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-06	1.E-07	Should come with certificate and commercial document. Risks are lower than those associated with personal imports

Feed factory	1.E+02	1.E-06	1.E-07	Unlikely to pose a risk - contaminated vegetable matter poses the highest risk
Domestic animal/ backyard farms	1.E+02	1.E-05	1.E-06	Domestic animals and backyard farms are less controlled comparatively to other pig farms. There a is higher likelihood of animals being fed food scraps
Environment	1.E+02	1.E-06	1.E-07	Ill Discarded food (meat products)
Wildlife	1.E+02	1.E-06	1.E-07	Direct contact between the disease agent and the wildlife is highly unlikely.
Animal gathering	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)
Farms Breeders	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)
Outdoor Finishers	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)
Indoor Finishers	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)

Table 16.3 EU Negative

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	1.E+02	1.E-07	1.E-08	No comments recorded
Livestock Vehicles	1.E+02	1.E-07	1.E-08	Improper Cleansing & Disinfection activity on a vehicle coming from a unknown virus source
Domestic residence	1.E+05	1.E-07	1.E-08	No comments recorded
Petting zoo/pet shop	1.E+02	1.E-04	1.E-05	Import levels are very low; with animals and products subjected to normal import rules
Veterinarian./fieldsmen / other intervenient	1.E+02	1.E-04	1.E-05	Veterinarian contaminated from an unknown virus source.
Waste disposal plant	1.E+05	1.E-07	1.E-08	Relies on source
Food markets / Retailers / Restaurants/Caterer	1.E+05	1.E-07	1.E-08	The sole concern is with internal controls in countries with regions that have CSF
Feed factory	1.E+02	1.E-07	1.E-08	Virtually zero - Most banned
Domestic animal/ backyard farms	1.E+02	1.E-07	1.E-08	From CSF free countries/region
Environment	1.E+02	1.E-07	1.E-08	Transmission levels between EU countries and the environment within UK is near zero
Wildlife	1.E+02	1.E-07	1.E-08	No comments recorded
Animal gathering	1.E+02	1.E-07	1.E-08	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)

Farms Breeders	1.E+02	1.E-06	1.E-07	No comments recorded [Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)]
Outdoor Finishers	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)
Indoor Finishers	1.E+02	1.E-06	1.E-07	Low throughput (there should be no throughput) from diseased areas (certification is the main barrier)

Table 16.4 Border Inspection Post

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	1.E+02	1.E-03	1.E-05	*Values not used for simulation No comments recorded
Slaughterhouse /meat processing plants	1.E+02	1.E-04	1.E-06	No comments recorded
Livestock Vehicles	1.E+02	1.E-05	1.E-07	No comments recorded
Domestic residence	1.E+02	1.E-04	1.E-06	Theft from ports is a concern
Petting zoo/pet shop	1.E+02	1.E-05	1.E-07	No comments recorded
Veterinarian./fieldsmen/ other intervenient	1.E+03	1.E-04	1.E-06	Risk is higher when dealing with live animal consignments that with other products
Waste disposal plant	1.E+02	1.E-04	1.E-05	No comments recorded
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-03	1.E-04	Risk results form a more permissive regulations
Feed factory	1.E+02	1.E-08	1.E-08	Legislative barriers should reduce risk to a minimum
Domestic animal/ backyard farms	1.E+02	1.E-06	1.E-08	No comments recorded
Environment	1.E+02	1.E-03	1.E-04	No comments recorded
Wildlife	1.E+02	1.E-06	1.E-08	No comments recorded
Animal gathering	1.E+02	1.E-06	1.E-08	No comments recorded
Farms Breeders	1.E+02	1.E-06	1.E-08	No comments recorded
Outdoor Finishers	1.E+02	1.E-06	1.E-08	No comments recorded
Indoor Finishers	1.E+02	1.E-06	1.E-08	No comments recorded

Table 16.5 Environment

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	NA
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+05	1.E+00	1.E-01	Contact between vehicles and fomites (water/soil). Vehicles are subjected to low levels of bio security unless an outbreak occurs
Domestic residence	NA	NA	NA	NA
Petting zoo/pet shop	NA	NA	NA	NA
Veterinarian./fieldsmen / other intervenient	1.E+03	1.E-04	1.E-05	No comments recorded
Waste disposal plant	NA	NA	NA	NA
Food markets / Retailers / Restaurants/Caterer	NA	NA	NA	NA
Feed factory	1.E+02	0.E+00	0.E+00	No Comments recorded
Domestic animal/ backyard farms	1.E+03	1.E+00	1.E-01	Backyard holding have low levels of bio-security, ill-informed visitors
Environment	NA	NA	NA	NA
Wildlife	1.E+02	1.E-07	1.E-08	Wild boar may gain access to waste bins on picnic sites is a potential risk. Physical barriers alone prevent transmission.
Animal gathering	1.E+02	1.E-06	1.E-08	No Comments recorded
Farms Breeders	NA	NA	NA	NA
Outdoor Finishers	1.E+03	1.E+00	1.E-01	No Comments recorded

Indoor Finishers	1.E+02	1.E-02	1.E-03	Potential contamination of boreholes and vermin

Table 16.6 Wildlife [Wild boar]

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	1.E+02	1.E-06	1.E-08	*Values not used for simulation. Laboratory admissions
Slaughterhouse /meat processing plants	1.E+02	1.E-02	1.E-03	Infected wild boar sent to slaughter or enter premises
Livestock Vehicles	1.E+02	1.E-06	1.E-07	Transmission from infected animals to the wild animal boar [Barriers include - behaviour of wild boar and location of vehicles]
Domestic residence	1.E+02	1.E-03	1.E-04	Contact between wild boar population and human population [feeding the wild boar]
Petting zoo/pet shop	1.E+03	1.E-01	1.E-02	Contact with farmed animals is dependent of the wild boar population in the area route
Veterinarian./fieldsmen/ other intervenient	1.E+02	1.E-01	1.E-03	Wild boar population shot by farmer and opportunity for transmission during treatment
Waste disposal plant	1.E+02	1.E-01	1.E-02	Wild boar carcasses end up in a landfill
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-03	1.E-03	Illegal sale of wild boar in butchers/ restaurant trade
Feed factory	1.E+02	1.E-05	1.E-07	Hasap legislation makes this route unlikely
Domestic animal/ backyard farms	1.E+03	1.E-01	1.E-02	No comment recorded
Environment	1.E+05	1.E+00	1.E-01	Environmental contamination by the wild boar population
Wildlife	NA	NA	NA	NA

Animal gathering	1.E+02	1.E-05	1.E-06	Legislation and physical bio safety barriers reduce risk of transmission
Farms Breeders	1.E+04	1.E-01	1.E-02	Wild boar can enter the breeding unit or young domestic pigs escape from premises into the environment and back [Evidence from Belgium]
Outdoor Finishers	1.E+04	1.E-01	1.E-02	Wild boar can enter the breeding unit or young domestic pigs escape from premises into the environment and back [Evidence from Belgium]
Indoor Finishers	1.E+03	1.E-03	1.E-04	Wild boar can enter the breeding unit or young domestic pigs escape from premises into the environment and back [Evidence from Belgium]

Table 16.7 Laboratories

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+02	1.E-02	1.E-03	Cleansing and disinfection of vehicles often not done properly
Domestic residence	1.E+04	1.E-05	1.E-06	No comments recorded
Petting zoo/pet shop	NA	NA	NA	NA
Veterinarian./fieldsmen / other intervenient	1.E+02	1.E-04	1.E-05	No comments recorded
Waste disposal plant	1.E+04	1.E-06	1.E-07	No comments recorded
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-06	1.E-08	Respect for the Good Laboratory Practice [GLP] reduces greatly the risk of transmission
Feed factory	1.E+02	1.E-06	1.E-08	Unlikely [no comments recorded]
Domestic animal/ backyard farms	1.E+03	1.E-05	1.E-06	Trained that are aware of the risks and signs on undertaking not to contact with susceptible species
Environment	1.E+03	1.E-05	1.E-06	No comments recorded
Wildlife	1.E+02	1.E-06	1.E-07	No comments recorded
Animal gathering	NA	NA	NA	NA
Farms Breeders	NA	NA	NA	NA
Outdoor Finishers	NA	NA	NA	NA
Indoor Finishers	NA	NA	NA	NA

Table 16.8 Pet Shop/Petting Zoo

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	1.E+03	1.E-05	1.E-08	No comments recorded
Livestock Vehicles	1.E+03	1.E-03	1.E-08	Vehicle movements to zoos are well controlled
Domestic residence		1.E-03	1.E-08	The main risk of transmission lie on the 1) Zoo visitors, and 2) the animal keepers [higher threat]
Petting zoo/pet shop	NA	NA	NA	NA
Veterinarian./fieldsmen / other intervenient	1.E+03	1.E-05	1.E-08	Bio-safety protocol and personal hygiene
Waste disposal plant	1.E+03	1.E-02	1.E-04	Transport of animal carcasses for disposal and washing down of vehicles
Food markets / Retailers / Restaurants/Caterer	1.E+04	1.E-05	1.E-08	On site restaurant and caterers can be of concern
Feed factory	1.E+03	1.E-05	1.E-08	The main transmission route of is via people
Domestic animal/ backyard farms	1.E+03	1.E-05	1.E-08	The main transmission route of is via people
Environment	1.E+04	1.E-05	1.E-08	The main transmission routes are 1) Disposal of various food goods and feed, 2) Footwear and 3) Transports
Wildlife	1.E+04	1.E-05	1.E-08	The main transmission routes are 1) Disposal of various food goods and feed, 2) Footwear and 3) Transports
Animal gathering	NA	NA	NA	NA

Farms Breeders	NA	NA	NA	NA
Outdoor Finishers	NA	NA	NA	NA
Indoor Finishers	NA	NA	NA	NA

Table 16.9 Food Markets/Restaurant/Caterer

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*values not used for simulation NA
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+02	1.E-03	1.E-05	The main transmission routes are the 1) drivers lunch, and a 2) contaminated trailer
Domestic residence	1.E+05	1.E-07	1.E-08	No comments recorded
Petting zoo/pet shop	1.E+03	1.E-01	1.E-03	Transmission routes creating concern are 1) packed lunch 2) Accidental contamination of Bakery waste 3) risk of restaurant waste.
Veterinarian./fieldsmen / other intervenient	NA	NA	NA	NA
Waste disposal plant	1.E+05	1.E-01	1.E-05	Trading standards reduce risk of transmission through legal movements there are however no physical or legal barriers against. Waste disposal technologies such as composting/Anaerobic digestion may contribute to spreading the disease (Paul Gale,)
Food markets / Retailers / Restaurants/Caterer	NA	NA	NA	NA
Feed factory	1.E+03	1.E-01	1.E-05	Accidental contaminations of an on-farm mixers [illegal use for pet food production]
Domestic animal/ backyard farms	1.E+03	1.E-01	1.E-03	Catering waste used to feed hobby pig/micro pigs by keepers
Environment	1.E+02	1.E+00	1.E-01	Ill disposal of food goods such as throwing a sandwich

Wildlife	1.E+03	1.E-02	1.E-08	Concerning routes of transmission may involve 1) scavengers (Foxes rummaging through waste bins), 2) accidental contamination and 3) feeding birds
Animal gathering	NA	NA	NA	NA
Farms Breeders	1.E+03	1.E-01	1.E+03	Concerns involve an accidental contamination/illegal collection and non-assured commercial farms, smaller producers (cull sow fattening)
Outdoor Finishers	1.E+03	1.E-01	1.E+03	Concerns involve an accidental contamination/illegal collection and non-assured commercial farms, smaller producers (cull sow fattening)
Indoor Finishers	1.E+03	1.E-01	1.E+03	Concerns involve an accidental contamination/illegal collection and non-assured commercial farms, smaller producers (cull sow fattening)

Table 16.10 Feed factory

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	1.E+04	1.E-08	1.E-08	*values not used for simulation - samples for analysis
Slaughterhouse /meat processing plants	1.E+03	1.E-07	1.E-08	Concerns reside in 1) personnel movements and 2) farmer owned Trailers for transport of animal to slaughter
Livestock Vehicles	1.E+04	1.E-06	1.E-07	Farmer owned livestock vehicles/tractors used to transport animals feed to farms
Domestic residence	NA	NA	NA	NA
Petting zoo/pet shop	1.E+04	1.E-08	1.E-08	Vehicles and personnel present the highest risk of transmission risk
Veterinarian./fieldsmen / other intervenient	1.E+05	1.E-07	1.E-08	Feed lorries and the lorries drivers present the highest risk
Waste disposal plant	1.E+05	1.E-05	1.E-08	Wasted disposal techniques involve composting. Contamination of adjacent fields to the composting pile and subsequent contamination fields
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E-07	1.E-08	Personnel behaviour is the main concern
Feed factory				
Domestic animal/ backyard farms	1.E+05	1.E-07	1.E-08	Personnel behaviour is the main concern
Environment	1.E+02	1.E-08	1.E-08	Accidental contamination of the environment by food.
Wildlife	1.E+02	1.E-08	1.E-08	No comments recorded

Animal gathering	1.E+02	1.E-05	1.E-08	No comments recorded
Farms Breeders	1.E+05	1.E-05	1.E-08	Concerns include on farm mixing of feed, were waste from factories and/or supermarket are included. It does not does not include the risk of farm to farm contamination by a feed lorry.
Outdoor Finishers	1.E+05	1.E-06	1.E-08	Compound feed not be contaminated with CSF. It does not does not include the risk of farm to farm contamination by a feed lorry.
Indoor Finishers	1.E+05	1.E-06	1.E-08	Compound feed not be contaminated with CSF. It does not does not include the risk of farm to farm contamination by a feed lorry.

Table 16.11 Domestic residence

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+02	1.E+00	1.E-03	The main concerns are the lorry driver [lunch pack up]. Pig gain access to the sandwich
Domestic residence				
Petting zoo/pet shop	1.E+03	1.E+00	1.E-01	Illegal feeding of pigs [sandwiches]
Veterinarian./fieldsmen / other intervenient	1.E+02	1.E-02	1.E-03	Contamination of Veterinary facilities by pet pigs/ the car park is also a concern
Waste disposal plant	1.E+02	1.E+00	1.E-02	Disposal of dead pigs using a domestic waste bin. Followed by disposal of the carcass at an open air landfill
Food markets / Retailers / Restaurants/Caterer	NA	NA	NA	NA
Feed factory	1.E+02	1.E-08	1.E-08	Risk is close to null
Domestic animal/ backyard farms	1.E+02	1.E-01	1.E-03	Micro and domestic pigs feed waste food sent back to backyard farm
Environment	1.E+02	1.E-02	1.E-04	Improper disposal of pig carcasses, with these being buried or abandoned. The release or escape of live pigs

Wildlife	1.E+ 03	1.E+00	1.E-01	Wildlife scavenging waste food from bins or leftover food dumped in the country side (foxes may carry off but then wild boar may get access). Unwanted pet pigs released in the countryside.
Animal gathering	1.E+ 02	1.E-02	1.E-03	Visitors feeding animals at shows (heavier controls/lowers flows than petting zoo)
Farms Breeders	1.E+ 02	1.E-04	1.E-05	Migrant workers are of concerned. Disease can be transported by a packed up lunches and/or fomites (clothes, footwear (controls are in place on farm to avoid transmission)
Outdoor Finishers	1.E+ 02	1.E-02	1.E-03	People feeding picnic food to outdoor pigs out walking. Contact between farmed animals Unwanted pet pigs released into other countryside 3) Migrant workers - post food access by pigs
Indoor Finishers	1.E+ 02	1.E-04	1.E-05	Migrant workers are of concerned. Disease can be transported by a packed up lunches and/or fomites (clothes, footwear (controls are in place on farm to avoid transmission)

Table 16.12 Veterinarian/Fieldsman/other intervenient

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	1.E+02	1.E-06	1.E-08	No comment recorded
Laboratories	1.E+04	1.E+00	1.E+00	*Values not used for simulation Submissions
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+05	1.E-06	1.E-08	No comment recorded
Domestic residence	1.E+05	1.E+00	1.E-01	No comment recorded
Petting zoo/pet shop	1.E+05	1.E+00	1.E-01	Bio-safety should apply [Barriers are boot dips] however unlikely to have wash on/wash off or specific boot dips
Veterinarian./fieldsmen / other intervenient	NA	NA	NA	NA
Waste disposal plant	1.E+03	1.E+00	1.E-01	No comment recorded
Food markets / Retailers / Restaurants/Caterer	1.E+04	1.E+00	1.E-02	No comment recorded
Feed factory	1.E+04	1.E+00	1.E-03	Concern resides in the movements of fieldsman [a group inclusive of personnel working in the feed industry]
Domestic animal/ backyard farms	1.E+05	1.E+00	1.E-01	Concern resides in the movements of fieldsman with the assumption that the people working on these farms are classed as fieldsman
Environment	1.E+05	1.E-03	1.E-05	No comment recorded

Wildlife	1.E+0 2	1.E+00	1.E-01	No comment recorded
Animal gathering	1.E+0 5	1.E+00	1.E+00	Concern resides in the movements of fieldsman and Veterinarians - barrier failure higher for fieldsman then a more informed Veterinarian
Farms Breeders	1.E+0 5	1.E-05	1.E-07	The range of likelihood of transmission is varies with the different types of unit
Outdoor Finishers	1.E+0 5	1.E-01	1.E-04	No comment recorded
Indoor Finishers	1.E+0 5	1.E-01	1.E-04	No comment recorded

Table 16.13 Slaughterhouse/meat processing plants

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	1.E+02	1.E+00	1.E+00	*Values not used for the simulation - samples sent to laboratory
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	1.E+05	1.E-03	1.E-05	Legal routes - hauliers (C &D) Farmers are a less likely mode of transmission but link to premises.
Domestic residence	1.E+05	1.E-06	1.E-08	Staff is the main concern [division between clean and dirty area as well a dedicated working clothing/boots reduce risk. Illegal movement of meat products from smaller establishments
Petting zoo/pet shop	1.E+02	1.E-06	1.E-08	Concerns are on the illegal use of by-products
Veterinarian./fieldsmen / other intervenient	1.E+05	1.E-06	1.E-08	Veterinarians working at the slaughter house are expected to have and implement a high level of bio security awareness. Separation between dirty and clean areas
Waste disposal plant	1.E+05	1.E-02	1.E-03	The presence of transport skips in yards and accessible to birds how can steal infected material
Food markets / Retailers / Restaurants/Caterer	1.E+05	1.E-06	1.E-08	Very low risk of meat from slaughterhouse or cutting plant escaping on the way to retailers
Feed factory	1.E+02	1.E-06	1.E-08	Illegal movement without a foreseeable gain. Sabotage
Domestic animal/ backyard farms	1.E+01	1.E-05	1.E-07	Concerns are the illegal use of offal and occasional live animals leaving to be moved to the farm (5-10 per year)

Environment	1.E+05	1.E-06	1.E-07	Risk are washed water from lairise and straw /bedding from vehicles
Wildlife	1.E+02	1.E-06	1.E-08	Very low risk of pigs living in the wild getting into a dirty lairage
Animal gathering	1.E+02	1.E-06	1.E-08	Illegal movement without a foreseeable gain. Sabotage
Farms Breeders	1.E+02	1.E-06	1.E-08	Illegal movement without a foreseeable gain. Sabotage
Outdoor Finishers	1.E+02	1.E-04	1.E-06	Escape, rodents/birds dropping scavenged waste. Man-made movements are illegal without a foreseeable gain. Sabotage
Indoor Finishers	1.E+02	1.E-06	1.E-08	Illegal movement without a foreseeable gain. Sabotage

Table 16.14 Livestock Vehicles

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	NA	NA	NA	NA
Livestock Vehicles	NA	NA	NA	NA
Domestic residence	1.E+05	1.E-03	1.E-05	The concerns are the drivers and farmers no legal barriers exist - common sense alone
Petting zoo/pet shop	1.E+02	1.E-06	1.E-08	No comments recorded
Veterinarian./fieldsmen / other intervenient	1.E+05	1.E-02	1.E-06	Vehicles attend market/shows/farms and may have driver attending animals on vehicles. No barriers exist - common sense alone [bio safety awareness places Veterinarians on one end of the scale and drivers on the other]
Waste disposal plant	1.E+04	1.E-05	1.E-07	There are no legal barriers avoiding this movement but very low risk is expected
Food markets / Retailers / Restaurants/Caterer				
Feed factory	1.E+04	1.E-04	1.E-07	Farm vehicles go to feed mills to collect feed where tractor units are common between livestock trailers and feed trailers. Also common sense the only barrier to transmission.
Domestic animal/ backyard farms	1.E+03	1.E-02	1.E-04	Uncontrolled and unaware people make this moves
Environment	1.E+03	1.E-06	1.E-08	Spillage from vehicle and standing dirty vehicle attracting rodents etc.

Wildlife	1.E+ 02	1.E-06	1.E-08	Very tenuous link between pigs living in the wild getting access to the dirty vehicle
Animal gathering	1.E+ 05	1.E-05	1.E-07	Hauliers and farmers are the greatest concerns. Low volume of pigs sold at market, however higher for animal shows
Farms Breeders	1.E+ 04	1.E-06	1.E-08	These units are very bio secure minded
Outdoor Finishers	1.E+ 05	1.E-05	1.E-07	High bio security in big operations
Indoor Finishers	1.E+ 05	1.E-05	1.E-07	High bio security in big operations

Table 16.15 Domestic animals/Backyard Farms

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	1.E+02	1.E+00	1.E-01	Illegal supply of home killed meat
Laboratories	NA1.E+02	1.E-06	1.E-08	*Values not used during simulation Samples from backyard to lab
Slaughterhouse /meat processing plants	1.E+04	1.E-05	1.E-06	The controls in place at the slaughterhouse should prevent transmission
Livestock Vehicles	1.E+03	1.E+00	1.E-03	There is a wide range of unprepared vehicles used to transport pet pigs.
Domestic residence	1.E+02	1.E+00	1.E-04	Movement of pet pig form breeders to domestic residence and home killed meat to domestic residence
Petting zoo/pet shop	1.E+02	1.E-03	1.E-03	Re-homing of pet pigs moves for breeding/sharing boar etc.
Veterinarian./fieldsmen / other intervenient	1.E+02	1.E+00	1.E-06	Pigs taken to the Veterinary premises for treatment and movement of fieldsman
Waste disposal plant	1.E+02	1.E+00	1.E-01	Improper [illegal] disposal of pet pigs and leftover of home kill disposed in waste bin
Food markets / Retailers / Restaurants/Caterer	1.E+02	1.E+00	1.E-01	Illegal supply of home killed meat to markets and restaurants
Feed factory	1.E+02	1.E-03	1.E-03	Illegal supply of home kill by-products to pet food manufacturing
Domestic animal/ backyard farms	NA	NA	NA	NA
Environment	1.E+02	1.E+00	1.E-01	Pet pig owners abandoned/release pigs into the environment once to big escaped pigs 3) incorrect disposal of dead pigs and/or By products

Wildlife	1.E+ 02	1.E+00		Live and dead pigs abandoned/escaped pigs contact with wild boar 2) incorrect disposal of carcasses and/or by-products (home kill)
Animal gathering	1.E+ 03	1.E-01	1.E-01	Movement of animals to shows. Movement to markets (pigs markets) from this type of farm is increasing.
Farms Breeders	1.E+ 02	1.E-06	1.E-06	Very unlikely
Outdoor Finishers	1.E+ 03	1.E-03	1.E-04	Outdoor finishers could purchase pigs from backyard premises possibility of weaning pig coming into contact with an outdoor finisher
Indoor Finishers	1.E+ 02	1.E-06	1.E-06	Very unlikely

Table 16.16 Waste Disposal

Receptor node	Flow rate	Minimum	Maximum	Comments
Outside EU	NA	NA	NA	NA
EU [Positive]	NA	NA	NA	NA
EU [negative]	NA	NA	NA	NA
Border Inspection Post	NA	NA	NA	NA
Laboratories	NA	NA	NA	*Values not used for simulation NA
Slaughterhouse /meat processing plants	1.E+03	1.E-04	1.E-06	Illegal diversion of meat (waste) to food processing
Livestock Vehicles	1.E+03	1.E-01	1.E-02	Tractor units common to both operations and improper C&D due to cost of disinfectant [perception that metal corrodes metal, parts of vehicle difficult to reach, cost of time, no records of the amount of disinfectant purchased]
Domestic residence	NA	NA	NA	NA
Petting zoo/pet shop	NA	NA	NA	NA
Veterinarian./fieldsmen/ other intervenient	1.E+03	1.E-04	1.E-05	Veterinarians get everywhere as part of inspection regime. They visit diverse waste facilities and may be contaminated
Waste disposal plant	NA	NA	NA	NA
Food markets / Retailers / Restaurants/Caterer	NA	NA	NA	NA
Feed factory	1.E+04	1.E-01	1.E-02	Transport through birds
Domestic animal/ backyard farms	1.E+02	1.E-07	1.E-08	Concern that employees of waste the disposal establishment take home condemned products/contaminated feedstuff, transmission via employees clothes, footwear - more unlikely
Environment	NA	NA	NA	NA
Wildlife	NA	NA	NA	NA

Animal gathering	NA	NA	NA	NA
Farms Breeders	NA	NA	NA	NA
Outdoor Finishers	NA	NA	NA	NA
Indoor Finishers	NA	NA	NA	NA

17 ANNEX 3

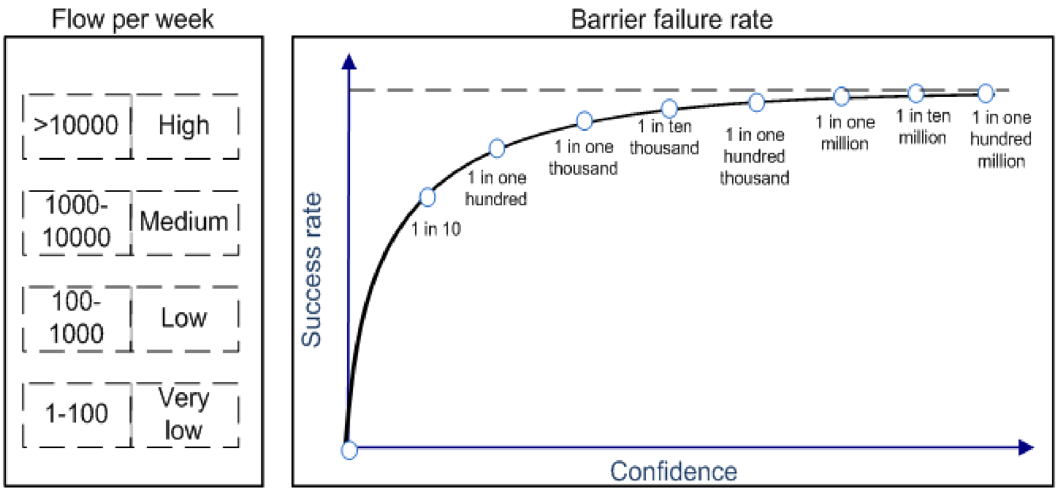
17.1 Elicitation form used in the second elicitation stage for Classic Swine Fever.

RPV21 Project - Risk Pathways & Vulnerabilities

Network Connections – Form

Source node: ____

Reception node: ____



Comments:

Figure 17.1 Form developed second elicitation stage workshop performed for studying the introduction of Classic Swine Fever.

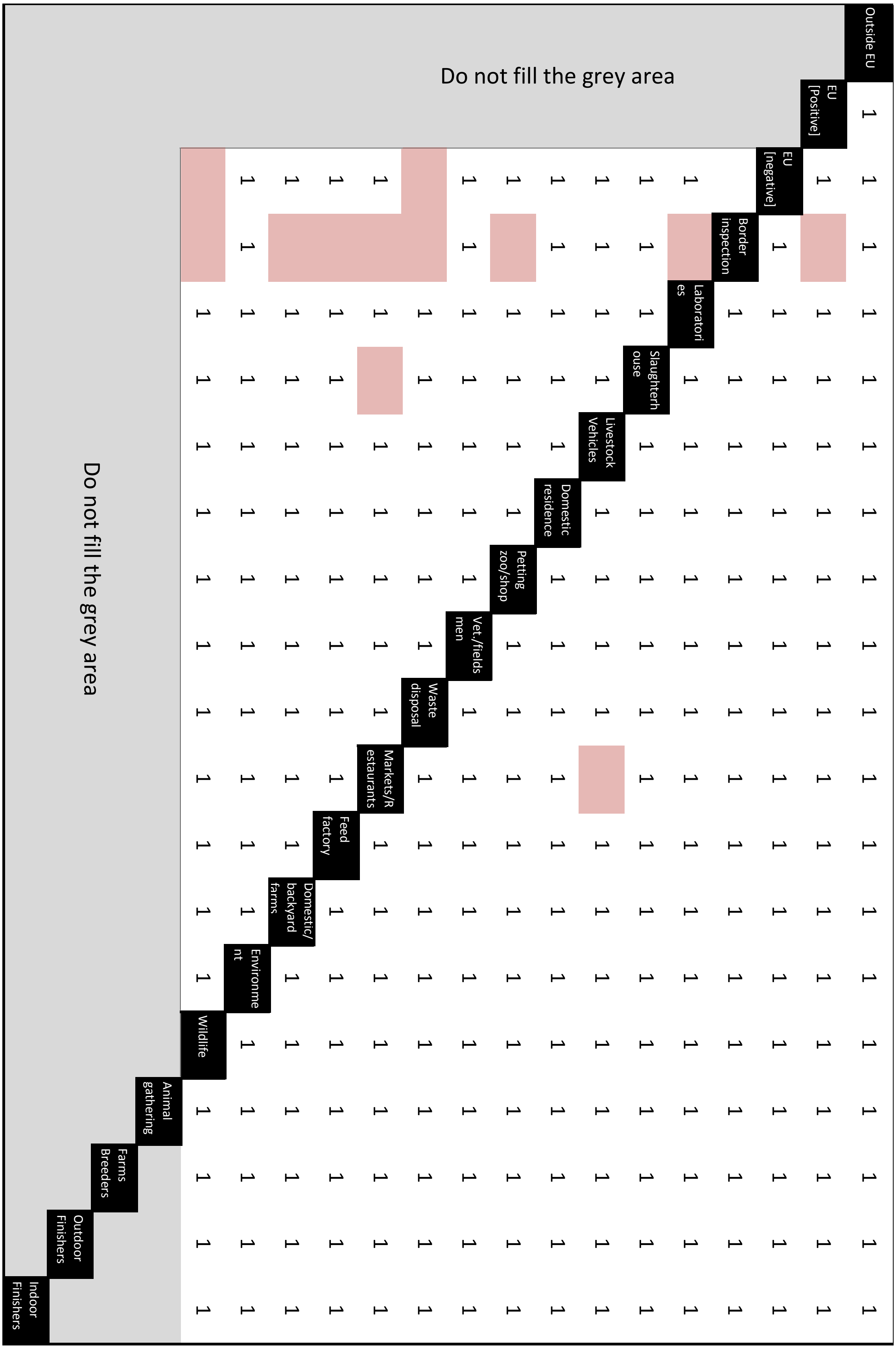


Figure 17.2 Collective output of the calibration exercises performed in the second elicitation stage workshop performed for studying the introduction of Classic Swine Fever.

18 ANNEX 4

Delegate list and questionnaire used for expert selection for the second elicitation stage workshop performed for studying the introduction of Classic Swine Fever.

Table 18.1 List of delegate invites

Delegate list: RPV21 workshop (Innovation Centre 29 June 2010)			
	Name	**Organisation**	**Role**
1	Elwyn Rees	ADAS	
2	Richard Hepple	Animal Health	Veterinary Services Manager
3	David Mouat	Animal Health	Head, Veterinary Exotic Notifiable Diseases Unit
4	David Harris	Animal Health	Veterinary Business Partner, Wales
5	Kate Sharpe	Animal Health	Head of Epidemiology
6	Brenda Foster	Animal Health	Veterinary Service Manager - Animal by-products
7		Animal Health	Veterinary Officer
8	Peter Anderson	Animal Health	Veterinary Officer
9	Marcus Bates	British Pig Association	CEO
10	Jeremy Adams	Cambridgeshire County Council	Trading Standards (LA responsible for animal by-products)
11	Michael Seton	City of London	Veterinary Service team leader City of London *Animal Reception Centre at Heathrow, The Ports (Tilbury & Thamesport) & covering animal health obligations for LAs in Greater London*
12	John Pascoe	Cornwall County Council	Trading Standards (Coastal LA concerned with smuggling)
13	Victor del Rio Vilas	Defra	Epidemiologist and Surveillance
14	John Bell	Defra	Livestock ID & Movements Policy
15	Teresa Mills	Defra	Lead imports policy adviser
16	Rolf Kluttig	Defra	Imports policy adviser

17	Julian West	Defra	Disease legislation and biosecurity
18	Edgar Black	Defra	Departmental Risk Co-ordinator
19	Lisa Smith	Defra	Animal Demography and Disease Informatics
20	Arik Dondi	Defra	Deputy Director, Policy
21	Bill Parish	Defra	ex-RPV Project Leader
22	Andy Paterson	Defra	Risk advice on horses and dangerous pathogens (representing Matt Hartley)
23	Mia Carbon	Defra	Veterinary Adviser for Imports
24	Jo Nettleton	HSE	Head of Biological Agents
25	Susie Child	LACORS	Animal Health and Welfare Policy Officer
26	Jon Averns	London Port Health Authority	EHO
27	Lewis Grant	MHS	
28	Zoe Davies	National Pig Association	Regions Manager
29	Eirian Williams	Somerset County Council	(LA with livestock market)
30	John Chaplin	Suffolk County Council	Trading Standards (LA with high density of livestock keepers)
31	Simon Rowell	Suffolk Port Health Authority	OV representing APHA
32	Mike Gregson	Oxfordshire County Council	Trading Standards (for Kevin Chesson)
33	Katherine Page	UK Border Agency	UK Border Agency Heathrow *illegal imports of animal products*
34	Amie Adkin	VLA	Senior Risk Analyst
35	Stan Done	VLA	Veterinary Investigation Officer
36	Helen Crooke	VLA	Head of Research on Pestiviruses
37	Richard Smith	VLA	Epidemiologist

18.1 Email invitation sent to workshop delegates (experts)

Thank you for agreeing to attend this workshop. To help us with the smooth running of the event, it would be helpful if we captured a little bit of information about you and your expertise. We would appreciate you completing the template below and sending it through to Edgar Black by close on Monday 28th. Some of this information will help us as we plan the group exercises.

Name	
Organisation	
Role	
Special dietary requirements	
Special access requirements	

We will be considering the main 'nodes' in the network of contacts that could allow the introduction of Classical Swine Fever into the country, potentially giving rise to a disease outbreak. Some of our group work will involve us looking in detail at the disease controls that are in place at each node, so it would be helpful if you could indicate which nodes your knowledge and experience relates to.

Network node	Knowledge or experience here? (Yes/No)

EU (disease-free countries)	
EU (disease-present countries)	
Outside EU	
Border inspection post	
Environment	
Wildlife	
Laboratories	
Zoos, pet shops	
Animal gatherings	
Retailers, restaurants, caterers, food markets	
Feed factory	
Domestic residence	
Vets, fieldsman, contractor	
Slaughterhouse, meat processing plant	
Livestock vehicles	
Domestic animals, backyard farms	
Waste disposal	
Farm (breeding units)	
Outdoor finishers	
Indoor finishers	

Table 18.2 Questionnaire for defining the experts' preferences

RPV21 workshop (Innovation Centre 29 June 2010)
Delegates sorted into 'node' groups

Node	**World (non-EU)**	**EU (disease)**	**Environment**	**Vet**	**Retailers**	**Vehicles**	**Home**	**Zoo**	**EU (free)**	**BIP**	**Backyard**	**Wildlife**	**Labs**	**Slaughter**	**Feed factory**	**Waste**
Name																
Andy Paterson	1			1		1	1			1	1	1	1			
Brenda Foster	1			1	1		1				1			1	1	1
David Mouat	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1
Helen Crooke	1	1	?						1			1	1			1
Jennifer Heald	1									1						1
Jeremy Adams					1	1	1	1			1			1	1	1
John Chaplin		1			1	1					1	1		1	1	1
John Pascoe						1										1
Julian West						1								1		
Kate Sharpe	1	1		1		1					1	1		1		1
Lewis Grant	1	1				1			1		1			1		1
Lisa Smith				1								1	1			
Marcus Bates	1				1		1				1					
Mia Carbon	1	1		1						1						
Mike Gregson						1					1			1	1	1
Mitch Sanders			1		1					1				1		
Peter Thomas				1				1		1	1		1	1		
Richard Hepple	1			1		1	1	1			1			1		1
Richard Smith				1		1								1		
Richard Stoddart	1	1		1				1			1		1	1	1	1
Rolf Kluttig	1	1							1	1						
Simon Rowell				1						1						
Stan Done	1	1		1		1			1				1			
Zoe Davies		1	1	1	1	1					1	1		1	1	1
John Bell														1		
Eirian Williams																
Susie Child																
Victor del Rio Vilas																

Table 18.3 Expert group compositions, developed for the second stage CSF elicitation – workshop.

[KEY] based on the information provides by the experts in the questionnaire.

Groups for activity 3

EU (free)	BIP	Wildlife	Backyard
Rolf Kluttig	Simon Rowell	Kate Sharpe	Marcus Bates
Lewis Grant	Mia Carbon	John Chaplin	Mike Gregson
Stan Done	Mitch Sanders	Lisa Smith	Jeremy Adams
			Richard Hepple

Labs	Slaughter	Feed factory	Waste
Andy Paterson	Julian West	Zoe Davies	John Pascoe
Helen Crooke	John Bell	Brenda Foster	Jennifer Heald
Peter Thomas	Richard Smith	David Mouat	Richard Stoddart

Groups for activity 4

World (non-EU)	EU (disease)	Environment	Vet
Jennifer Heald	Helen Crooke	Mitch Sanders	Simon Rowell
Kate Sharpe	Lewis Grant	Zoe Davies	Richard Smith
Rolf Kluttig	Stan Done	Helen Crooke	Lisa Smith
	Mia Carbon		

Home	Zoo	Retailers	Vehicles
Jeremy Adams	David Mouat	Brenda Foster	John Pascoe
Andy Paterson	Peter Thomas	John Chaplin	Julian West
Richard Hepple	Richard Stoddart	Marcus Bates	Mike Gregson

19 ANNEX 5

Outputs of the first stage of elicitation develop for the Import risk assessment of Foot and Mouth Disease. This activities developed in this stage provide a definition of the network nodes.

19.1 <u>Network nodes for Foot and Mouth Disease</u>

19.1.1 Node definitions

World (all remaining countries)/trading partners/Bilateral [Source] Countries outside the European Union, this includes third countries, trading partners and bilateral countries [New Zealand, Australia, Canada and USA]. There is no differentiation between countries where the disease is present; for ones were the disease is absent.

European Union and trading partners [Positive] [Source] Countries within the European Union currently without a disease free status. There is no differentiation between countries or regions within a country where the disease is present [national or regional trade limitations]

Laboratories [Source] Laboratories that have clearance to manipulate the Foot and mouth disease under consideration according to the SAPO regulations SOURCE NODE

European Union and trading partners [Negative – disease free status] Countries within the European Union that are considered under a disease free status. This includes countries benefiting with the European free market policy including recent Eastern Members, and Scotland and Wales (trading partners outside EU included). There is no differentiation from countries where the disease is not present from countries where the disease is present but not detected.

Border Inspection Post Border inspections posts [independent of location airport or nautical port]. Products legally imported from countries outside the EU, have to be check at a Borders inspection post. However illegal imports might bypass BIPs

Environment The environment encloses flora, water-bodies and other inanimate natural structures that can aid in the transmission of the disease agent and living creatures not included in terminal and wildlife population nodes. The node does not differentiate between pests and fomites: Pests include foxes, rodents and other potential FMD mechanical carriers; Fomites: any structure existing in the environment that can pose a potential threat in the transmission of the disease, such as grazing fields, water sources

Pet shops/ Zoo/ City farms/ Safari parks Entities possessing susceptible animals, located particularly within urban areas. Pet-shops and city farms present the opportunity for contact between the general human population and susceptible animals

Food markets / Retailers / Restaurants / Caterer Premises supplying food for human consumption for the general public (Super markets, local markets, restaurant and caterers)

Feed factory Facilities producing feed, feed additives, supplements and other products to be using in animal feeding to commercial farms and domestic animals

Domestic animals/backyard farms Livestock not usually breed for slaughter and small farms where livestock production is not the central activity, including, hobbyists and backyard farmers, and domestic susceptible species such as micro-pigs.

Human Population Section of the British population that does not have professional or regular contact with commercial animal farms (urban and rural population).

Vet\ Fieldsmen\ Workers This node encloses the section of the human population excluded from the human population node. There are included two particular groups. People of the human population that have a close contact or work commercial livestock farms (workers, migrant workers, owners and veterinary personnel)

Slaughterhouse \ food processing plants Slaughterhouses and meat products processing plants

Livestock vehicles Vehicles involved in the transport of live animals. The vehicle is the contaminated source, acting a fomite allowing for the transmission of the disease with the potential to infect healthy animals (include any straw used for bedding)

Animal gatherings within UK The node represents all sorts of animal gatherings within UK territory (Animals shows, Markets, national or international).

Waste disposal The node encloses all waste facilities allowed to with deal with potentially contaminated waste (e.g. landfills, incineration and rendering plants) within UK

Wildlife (Boar/Deer) Wildlife population susceptible to the diseases, within UK territory [wild boar and deer populations.

Pig indoor production units [Receptor] Indoor, intensive production of slaughter generation pigs (includes not only finishing units but also rearing and weaning units)

Pig outdoor production units [Receptor] Outdoor production of slaughter generation pigs (includes not only finishing units but also rearing and weaning units)

Pig breeding units [Receptor] Top of the pyramid, in-house breeding farms dedicated to the production of GGP, GP and sow lines. It also includes units that perform the complete cycle from reproduction to finishing. These are intensive production systems, characterised by a high bio-safety level. Multiplication units, pigs are not produced for slaughter.

Dairy production [Receptor] Dairy farms producing milk for milk products for human consumption (include milk for human consumption from goat and sheep farms).

Beef production [Receptor] Farms producing bull beef, steer and heifer for slaughter, without differentiation between extensive or intensive systems

Cattle breeding units [Receptor] Breeders for pedigree animals (high volume)

Sheep Outdoor production units [Receptor] Sheep farms producing animals for slaughter and/or for wool (animals bred for slaughter, collection of wool and rearing units); The vast majority of sheep farms are outdoors (hill, upland or lowland breeds)

Sheep breeding units [Receptor] Breeding units represents breeding farm for hill, upland and lowland breeds. These are characterised by higher levels of bio-security, when compared with commercial sheep farms including the replacement stock breed form within the flock

Mixed species farms [Receptor] Terminal node mixed species farm represent all units that produce more than one species, (includes different combination of pigs, cattle and sheep).

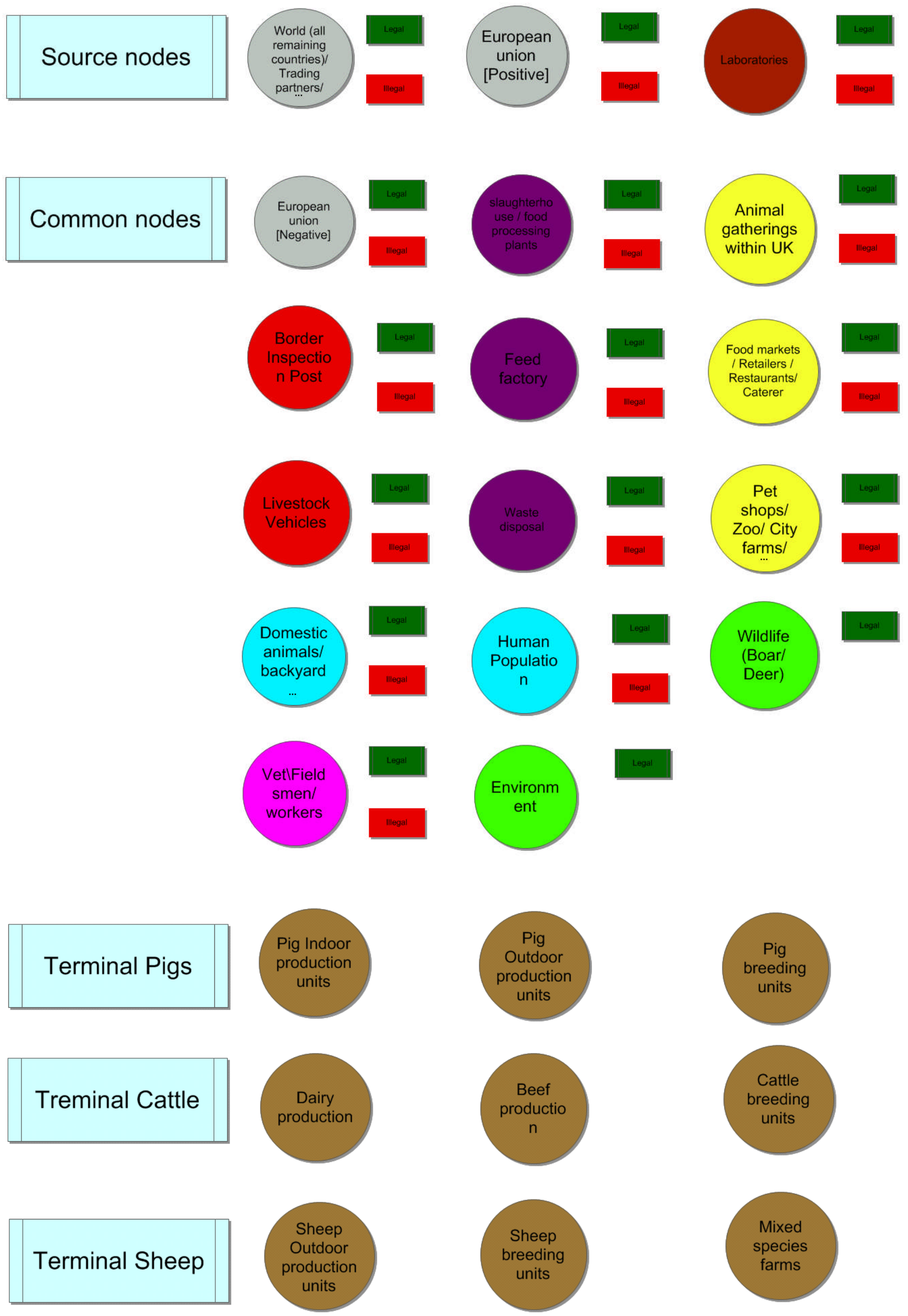


Figure 19.1 Collection of nodes develop in the first stage of elicitation applied to studying the introduction of FMD into England (Chapter 9)

[KEY] Source, common nodes and receptor are identified by the labels in the left; Colour schemes were used for guiding the assessors in terms of expertise needed.

20 ANNEX 6

20.1 <u>Elicitation form used in the second elicitation stage for Foot and Mouth Disease</u>

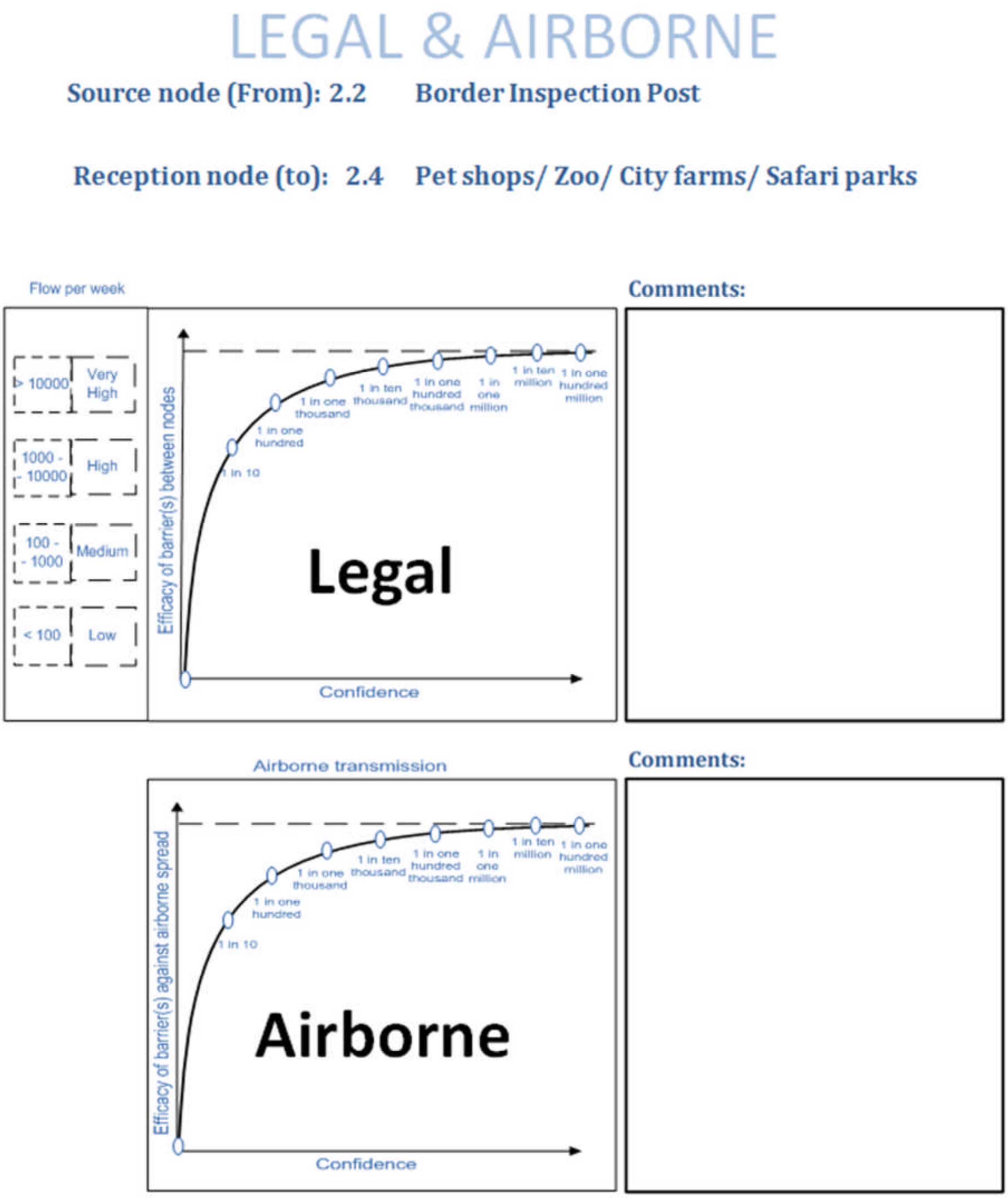
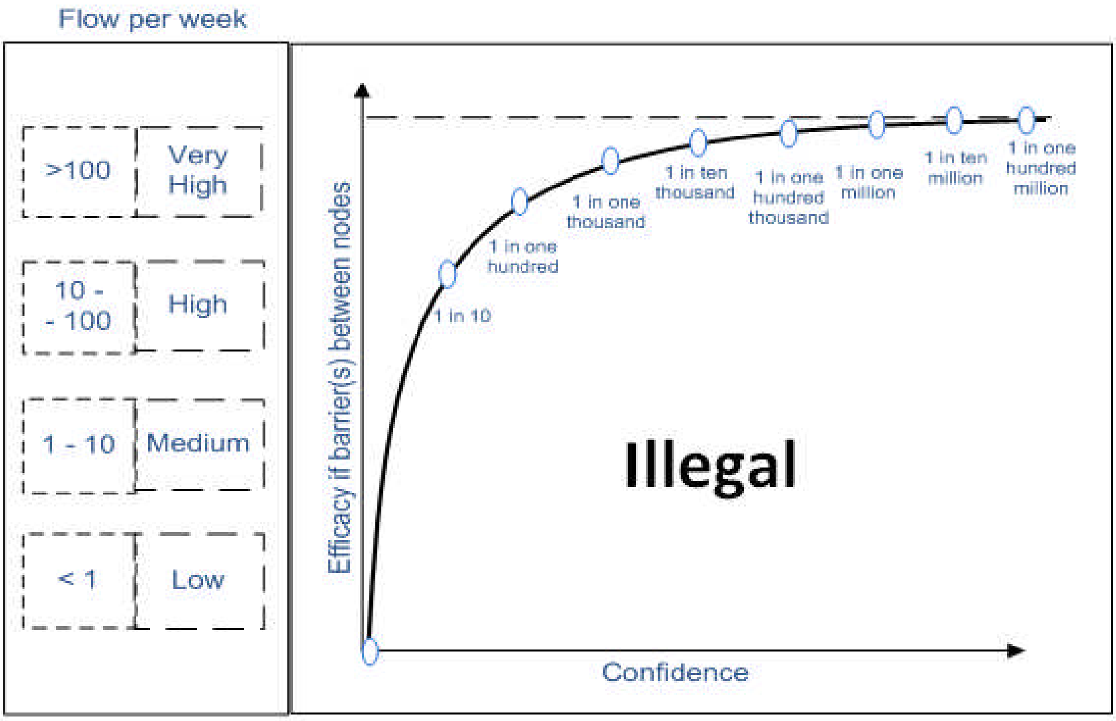


Figure 20.1 - Elicitation form for legal and airborne internode connections (even pages)

ILLEGAL

Source node (From): 2.2 Border Inspection Post

Reception node (to): 2.4 Pet shops/ Zoo/ City farms/ Safari parks



Comments:

Figure 20.2 - Elicitation form for illegal internode connections (odd pages)